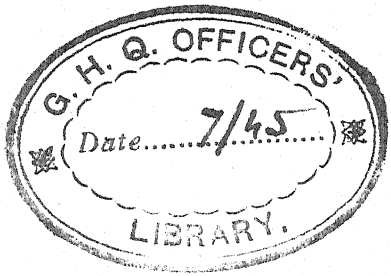
WEEDED OUT

WELDING HANDBOOK



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WELDING HANDBOOK

WEEDED OUT

1942

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EDITORIAL NOTE AND ACKNOWLEDGMENTS

This, the second edition of the Welding Handbook of the American Welding Society, is offered to the metal industries in response to a demand for general up-to-date information, in concise form, on the subject of welding. In order to best serve its purpose the volume has been prepared to cover, first, the physics and metallurgy of welding and the weldability of steels; second, the welding and allied processes; third, the materials used; fourth, training, inspection and safety; fifth, design considerations and testing of welding; and sixth, the applications of welding.

The aim has been to make sure that statements are accurate and recommendations authoritative. To this end, the Committee selected outstanding authorities, from those available in each field, as members of committees preparing the respective chapters. The desirability of impartial treatment of subject matter has been recognized by these committee members and the Handbook Committee.

This Handbook does not undertake to distinguish between processes or products that are patented and those that are not; and, of course, does not convey the right to use any that are patented.

While the Handbook Committee has endeavored to establish the reliability of the information given, it wishes to emphasize the fact that the opinions presented, and the terminology used, by the several groups of authors in their respective chapters, must be considered as individual expressions which are not necessarily endorsed by the Committee or the Society as a whole.

The text of this volume is generally arranged in handbook style. Nevertheless, the material has been arranged in a logical sequence with enough explanatory matter so that it may be used as a textbook in engineering schools and as a reference book in trade schools. The primary purpose, however, is to give engineers an authoritative up-to-date reference book on the technical phases of welding.

On behalf of the American Welding Society and itself, the Committee takes this opportunity to acknowledge its indebtedness to the hundreds of people who have assisted in the preparation of the chapters listed on pages VII & VIII.

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CHAPTER 1

PHYSICS OF WELDING*

The Nature of a Weld, the Approach to the Heat Problem, the Generation of Heat, Dissipation of Heat, Mechanical Problems, Heat Flow Problems

Foreword

WELDING involves more sciences and variables than any other industrial process, which may explain why most of those concerned are satisfied with a very crude understanding of its problems.

The principal sciences involved in welding are physics, chemistry and metallurgy. Of these the physics problems are the ones most often neglected and least understood, particularly from the quantitative point of view. These involve heat, mechanics, elasticity, plasticity, electricity and magnetism, as well as those very complicated and as yet little understood phenomena of the metallic arc. Testing and research work in this field require a knowledge of optics including polarized light, X-rays, X-ray diffraction, crystal theory and the constitution of matter.

This chapter is written for those who really wish to know the reason why and to acquire the habit of dealing with their problems quantitatively rather than qualitatively. It is not intended to imply that a welding engineer must or could be an expert in all of these branches of physics mentioned above. Moreover, it is obviously impossible to cover in this chapter, even superficially, all of these topics. However, it is hoped that the relatively simple applications discussed will help to stimulate a greater desire to understand the reason why as well as the habit of quantitative analysis Even a modest degree of progress toward this goal would mean more for the advancement of the welding art, and for the sound and rational solution of its many complicated problems, than any quantity of empirical data not rationalized and explained.

There are two ways of attacking problems involving as many variables as do those in the welding field.

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* Prepared by a committee consisting of C. A. Adams, E. G. Budd Mfg. Co., *Chairman;* G. E. Doan, Lehigh University; W. F. Hess, Rensselaer Polytechnic Institute; S. L. Hoyt, Battelle Memorial Institute; C. F. Lucks, Battelle Memorial Institute; E. M. Mahla, E. I. Du Pont De Nemours & Co.; D. Rosenthal, Massachusetts Institute of Technology; H. W. Russell, Battelle Memorial Institute.

(*a*) *The Empirical Method.*—This is the method most commonly employed and involves the making of many tests with many combinations of variables, in the effort to determine the effect of each by the process of elimination. Its chief difficulty lies in the fact that the number of experiments necessary for anything approaching dependable results is absolutely prohibitive. Moreover, if, as often happens, the experimenter is not fully aware of some of the significant variables which may vary from test to test without his knowledge, his results, when plotted against any given variable, yield what is commonly called a shotgun diagram rather than a smooth curve. In fact, this is the usual result in much of our so-called welding research, and is often due to the fact that the variables involved in the physics of the problem are not given due consideration, and that the quantitative analysis of these variables is not available to those concerned.

The results of such researches are not only obviously indefinite but often so conflicting that sound conclusions cannot be reached. Any doubt about this may be dispelled by reading some of the "Reviews of Welding Literature," published by the Welding Research Committee which present the conclusions and opinions in some cases of as many as 100 authors or research workers. The chief value of some of these reviews is to prove without a shadow of doubt that many of the researches reviewed are practically worthless and that there is great need for more sound fundamental or scientific research.

(*b*) *The Rational Method.*—This involves first a careful review of the problem with respect to all of the known variables, and the elimination of those variables which are known to be of minor importance. This demands quantitative familiarity with the phenomena and the laws involved. The next step is a rational formulation of the relationships between the significant variables, in so far as such formulation is possible, and the solution of the resulting equations. This is much more possible with regard to the problems involving physics than to those involving metallurgy, and it is this opportunity which is usually overlooked. In fact, the whole purpose of this chapter is to point out the possibilities in this field and to stimulate intelligent interest therein.

As previously stated, it often happens that such rational formulation must involve crude approximations and that the resulting solution may not be quantitatively accurate. However, in many such cases it is possible to couple the rational attack with experimental research, by means of which the coefficients and sometimes the exponents in the simplified equations can be determined to cover the range of interest. Moreover, such research rationally planned on the basis of a thorough analytical study will be found to involve a small fraction of the total number of experiments necessary in the purely empirical method. Also this rational solution is vastly more valuable from the practical point of view than the empirical, since it not only yields an understanding of the reason why, but also gives a better picture of the relative importance of the several variables involved and the degree in which they affect the result. For example, the result may be proportional to some power of a given variable, fractional or otherwise, and the knowledge of this fact often indicates definite limitations in the practical application of the process in question, or it may indicate the most logical method of removing those limitations. Also the rational solution may often be extended well beyond the range of the experimental research,

although this should be done only with due recognition of the possible effect of some of the minor variables which were neglected in the original solution.

The Nature of a Weld

Welding consists of the joining of two or more pieces of metal by the application of heat and sometimes of pressure. Welds accompanied by fusion are by far the most common, and these ordinarily do not require the application of pressure. When pressure is applied to a weld in which fusion takes place, the molten metal must be confined as within a solid mass of the metal. The weld may take place without fusion, if the metal is heated to such a temperature that a new system of grains is produced or grain growth of the existing system takes place. This latter condition usually requires the application of pressure, and is frequently referred to as a plastic weld, due to the fact that steel when heated above a critical temperature becomes plastic. Forge or other pressure welding is usually carried out at subfusion temperatures and mostly within the low white heat range. Electric resistance butt welding is almost always done at subfusion temperatures, whereas spot welding usually involves fusion of a considerable part of the thickness of the two sheets involved. However, actual fusion at the boundary is not absolutely essential in a spot weld, although it is very difficult to apply sufficiently accurate control and timing of the heat delivery, to reach the welding recrystallization temperature without passing over into the fusion range. Moreover, the surfaces would have to be free from all foreign substances as well as from any considerable oxide film.

In the case of welding dissimilar metals, welds may be brought about in which the metal with the lower melting point is melted and the metal with the higher melting point remains solid. In this case there is an alloy bond formed at the surface of the unfused metal. This type of weld may possess a great advantage in welding metals whose alloys form brittle compounds.

In making pressure welds where the welding takes place in the plastic condition, cleanliness of the abutting surfaces is a very important consideration since any oxidation or any other impurities on the surface may interfere with the attainment of a perfect bond. Careful facing of the surfaces to insure intimate contact over the area to be welded is often desirable. This may help to keep the surfaces free from contamination by the surrounding atmosphere, and is essential in the welding of high-strength materials of moderate ductility. Special atmospheres may also be used to protect the metal during heating.

In the welding of dissimilar metals, a mistake has frequently been made of attempting to fuse the two metals together, whereas a surface alloy bond would in many cases be much more satisfactory. This type of bond is common in the brazing of such metals as copper, steel and cast iron. It has also been found possible in electric resistance spot welding, by careful control, to melt one of the metals without fusing the other. In order to accomplish this it has been necessary to apply the heat in several steps, gradually approaching the melting point of the lower melting metal. In this way it is possible to avoid melting both metals.

APPROACH TO THE HEAT PROBLEM

A sound quantitative knowledge of thermal phenomena is absolutely essential to the solution of many important practical welding problems. Unfortunately, the theory of heat flow, particularly of transient heat flow, is not simple from the mathematical point of view. Moreover, both the thermal conductivity and specific heat, particularly at the high temperatures involved in welding, are difficult to obtain experimentally, and there is in consequence a considerable conflict between the data obtained by various experimenters.

Heat is a form of energy with exact equivalents in other forms of energy. Heat flows from a region of higher temperature to a region of lower temperature according to the same laws as those of electricity in flowing from a region of higher potential to a region of lower potential. The steady-state heat flow between the two faces of a slab of any material is proportional to the difference in temperature between the two faces of the slab and inversely to the thermal resistance of the path, which in this simple case is proportional to the length of the path, to the thermal resistivity of the material and inversely to the cross-section of the path, exactly as in the case of an electrical resistance. The following differences should be noted.

1. In the case of an electrical conductor, the leakage from the surface of the conductor into the air or insulation which may surround it is in most cases quite negligible, whereas in the case of a thermal conductor, particularly at high temperatures, it is very difficult to insulate it sufficiently to avoid a considerable heat leak from the surface. In other words, the ratio of the electrical resistivity of electrical insulators to that of electrical conductors is many times greater than the corresponding ratio in thermal cases.

2. Except in the case of highly inductive electric circuits, that is, those with a large electromagnetic inertia, and of circuits with high distributed capacitance, the steady state of the current is established almost instantly after the electromotive force or potential difference between the two ends of the path has been established. In the thermal case the steady state may not be reached for minutes, hours or weeks. The reason for this is that when heat starts to flow in at the hot end of the path, a part and often a considerable part is absorbed in raising the temperature of the zone into which it flows. It is only after the temperature of each zone has reached the steady state that this absorption of heat stops. Thus, if one end of a uniform bar one foot long, having perfectly insulated sides (this is practically impossible), were suddenly raised to a temperature of 1000°F., it would be some time before any increase in temperature took place at the far end of the bar and a much longer time before the temperature of the far end approached closely to that of the hot end, even if the far end and the side walls were perfectly insulated. This would be analogous to an electric circuit which is made up of a lot of resistors connected in series, and shunted by capacitors, but not at all similar to a simple electrical conductor of uniform section. In fact, by a proper selection of constants, the capacitor-resistor combination can be made to behave electrically in exactly the same manner as the side-insulated bar behaves thermally, although the time necessary to reach the steady state may differ without affecting the equivalence.

The amount of heat absorbed by any thin slice or zone of the bar, due to a given increase in temperature, is proportional to what is commonly called the specific heat of the material. The higher the specific heat, the more will be the heat absorbed in transit and the longer will it take for the steady state to be reached, other things being equal. Also the higher the thermal resistivity the longer will be the transient period. The specific heat corresponds to the shunted capacitance per unit length in the analogous electrical circuit and the thermal resistivity to the resistance per unit length. There is nothing in the thermal problem which is analogous to the inductance or electromagnetic inertia of an electrical circuit.

The mathematics of this simple bar problem is by no means elementary and would be still less so if the normal practical boundary conditions were taken into account, under which heat is escaping from the side walls of the bar at a rate depending upon its temperature, the nature and thickness of the insulation and the ambient temperature. In fact, the insulation will itself pass through a transient state which is usually much longer than that of the bar.

In brief, the factor which is chiefly responsible for the complication of transient thermal problems is the heat-absorbing capacity of the materials involved. Thus, during the transient state there are two independent variables—time and space. That is, the temperature at any point varies with time, and the temperature at any time varies throughout the length of the path.

This problem will be treated more quantitatively in another part of this chapter.

In spite of these complications and mathematical difficulties, it is often possible by dividing the path into finite slices and with simple although laborious calculations to get an approximate notion of the space and time distribution of temperature. Such calculations also help the investigator to acquire the habit of visualizing. They constitute the first step in quantitative thinking.

Lord Kelvin once said in substance if not in words, that mathematics is no earthly use until it has been turned into arithmetic. In other words, the quantitative perspective can be acquired only by repeated figuring, visualizing and checking by experiment.

Heat Units and Thermal Properties of Materials

Unit of Quantity

A *gram calorie* is the quantity of heat required to raise the temperature of one gram of water by one degree C., more exactly the average throughout the range from 0–100°C., since the specific heat of water is not absolutely constant at all temperatures.

A *kilogram calorie* is equal to 1000 gram calories. When the word calorie is used alone, it may be assumed to refer to the gram calorie.

A *British thermal unit* (Btu.) is the heat required to raise the temperature of 1 lb. of water 1°F., or the average between 32° and 212°F.

Heat Equivalents.—One Btu. = 252 gram calories = 778 ft.-lb. = 1055 joules or watt seconds. One gram calorie = 4.184 joules.

Rate of Flow.—The number of quantity units per unit of time. Calories per second, per minute or per hour, Btu.'s per second, per minute or per hour, or watts (joules per second). One Btu. per second = 1055 watts. One gram calorie per second = 4.184 watts.

Thermal Resistance.—The thermal resistance of any heat flow path is defined as the ratio of temperature difference between the ends of the path, to the rate of heat flow, i.e., to the number of heat units passing through the path in one unit of time. This is similar to electrical resistance which (for steady currents) is equal to the ratio of the difference of electrical potential between the ends of the path to the current flowing through it, i.e., the resistance in ohms is equal to the potential difference in volts divided by the current in amperes.

Unfortunately, in the thermal case there are two temperature scales (Fahrenheit and Centigrade, F. and C.), two heat units (Btu. and calories), and three time units (seconds, minutes and hours). Although there is no universally employed unit of thermal resistance, the one most commonly employed in scientific literature is degrees Centigrade per calorie per second.

Thermal Resistivity.—The thermal resistivity of any material is defined as the thermal resistance between opposite faces of a unit cube of that material. This introduces another base unit, that of length, which may be one centimeter, one inch or one foot. Thus, there are many possible combinations of these basic units in which thermal resistivity might be expressed, e.g., many heat engineers employ the following combination. Thermal resistivity is the difference in temperature in degrees F. necessary to drive one Btu. per hour through a slab (of the material in question) one inch thick and one foot square.

The simplest and most convenient terminology is that in which thermal resistance is defined as the degrees C. per watt, since the watt is one joule per second and already a rate of flow. Moreover, the corresponding unit of resistance has the simple label of a thermal ohm. That is, a heat path is said to have a resistance of one thermal ohm when it takes a difference of temperature between its ends of one degree C. to drive one watt of heat flow through it in the steady state.

Similarly, the *thermal resistivity* is the thermal ohms per centimeter cube of the material under consideration.

The use of this terminology is increasing rapidly and is particularly well adapted to welding problems where the source of heat is so often electrical energy.

Thermal Conductivity is the reciprocal of thermal resistivity. It is thus the watts per degree C. per centimeter cube or the thermal mhos per centimeter cube. Most of the data to be found in scientific literature give the thermal conductivity in calories per degree C. per centimeter cube, but this can be converted to thermal mhos (watts per degree C.) by multiplying by 4.184.

All calculations will be made by the use of thermal resistance rather than conductance. Moreover, since most welding engineers are more concerned with inches and Fahrenheit degrees than with centimeters and Centigrade degrees, resistivities and other thermal properties will be presented in the more familiar units. The following symbols will be employed.

Thermal Resistance—Symbols and Data

r_t = Thermal resistance in thermal ohms. Degrees C. per watt.
r_t'' = Thermal resistance in thermal ohms. Degrees F. per watt.

$$r_t'' = 1.8 r_t$$

ρ_t = Thermal resistivity in thermal ohm-cm. Degrees C. per watt per cm. cube.
ρ_t'' = Thermal resistivity in thermal ohm-in. Degrees F. per watt per in. cube.

$$\rho_t'' = 0.71 \rho_t$$

Although resistance and resistivity, rather than conductance and conductivity will be used, conductivity values are also given in Table 1, for purposes of comparison with other data, which comparison will often disclose considerable differences, since accurate determinations are very difficult to make.

γ_{tc} = Thermal conductivity in calories per second per degree C. per cm. cube.
γ_{tw} = Thermal conductivity in watts per degree C. per cm. cube.

$$\gamma_{tw} = 4.184 \gamma_{tc} \qquad \gamma_{tw} = \frac{1}{\rho_t}$$

Since ρ_t varies with temperature, values are given at two temperatures in Table 1. It usually increases with temperature, but decreases in aluminum and in 18–8 stainless steel.

Thermal Resistance of a Heat Path.—If the path has a constant cross-section of s square inches and a length of L inches and is composed of a material with a resistivity ρ_t'', its thermal resistance will be $r_t'' = \rho_t''(L/s)$ just as in the case of electrical resistance. If the cross-section is not constant, some equivalent value of L/s may be obtained by integration in those cases where that is possible, such as radial flow in a spherical or cylindrical shell, or by some means of approximation. This ratio L/s or its equivalent is sometimes referred to as the "geometric factor."

If a temperature difference of $T°$F. be maintained between the ends of such a path, the heat flow (steady state) will be

$$p = \frac{T}{r_t''} \text{ watts}$$

or

$$H = \frac{p}{1055} = \frac{T}{1055 r_t''} \text{ Btu. per second}$$

As a general example, consider the simple case of parallel heat flow through a metal slab. Assume the space temperature gradient (the drop in temperature per inch length of path) to be $T''°$F., and compute the heat flow in watts per square inch of path section. It is, $p'' = T''/\rho_t''$ since both L and s are unity. Or for low carbon steel $p'' = T''$ since $\rho_t'' = 1$ at low temperatures. For higher temperatures, ρ_t'' will increase and p'' decrease. If $T'' = 1000°$F. and $\rho_{t\,\text{avg.}}'' = 1.33$ (see Table 1), $p'' = 750$ watts per square inch. For stainless steel this would be 278 watts, for aluminum 3220 watts (more than ten times that for stainless steel) and for copper 5200 watts per square inch.

It should be noted that the gradient above assumed is one degree F. per mil (0.001 in.), whereas in spot welding thin sheets of stainless steel it may

Table 1

	γ_{tc}		γ_{tw}		ρ_t		ρ_t''		$K_e \times 10^6$	
TEMP., °F.	200°	932°	200°	932°	200°	932°	200°	932°	0°–100°	0°–1000°
Pure iron	0.18	0.11	0.75	0.46	1.33	2.17	0.94	1.54	6.5	...
Low carbon steel	0.17	0.10	0.71	0.42	1.41	2.38	1.0	1.66	7	8
High carbon steel	0.12	0.07	0.50	0.29	2.0	3.42	1.42	2.42	6.3	8
Stainless steel, 18 chromium–8 nickel	0.045	0.05	0.19	0.21	5.3	4.8	3.78	3.4	11	...
Aluminum	0.49	0.63	2.05	2.64	0.487	0.38	0.346	0.27	12.3	16
Copper	0.9	0.86	3.76	3.6	0.265	0.277	0.188	0.196	9.3	...

K_e is the coefficient of linear expansion in inches per inch per degree F.

be several hundred degrees F. per mil in very short-time welds. That is, the rate of heat flow in such a case might easily be 50 kw. per square inch of spot area.

Specific Heat.—This is defined as the ratio of the amount of heat necessary to raise the temperature of a given weight or mass of a material one degree, to that required to raise the temperature of the same mass of water one degree, at some specified temperature. It is therefore the number of heat units required to raise the temperature of a unit weight of the substance one degree, e.g., the calories to raise one gram of the substance one degree C., or the Btu.'s to raise one pound one degree F.

It is sometimes convenient to express this as joules per pound (or per cubic inch) per degree F. (or per degree C.), but these are not true specific heats, although proportional thereto.

Average values of specific heat are given in Table 2 over the range from 70°F. to the temperature of fusion. These average values are not exact, but close enough for practical purposes. As in the case of thermal resistivity, authorities differ materially.

Table 2

METAL	T_f	$T_f - T_a$	h_s	$(T_f - T_a)h_s$	H_1	H_f	$J_{lb.}$	J''	g
Pure iron	2795	2725	0.16	436	115	551	581,000	163,500	0.282
Mild steel	2775	2705	0.155	420	115	535	564,000	159,000	0.282
High carbon steel	2732	2662	0.15	400	115	515	543,000	153,000	0.282
Stainless steel 18–8	2665	2595	0.14	363	115	478	504,000	142,000	0.282
Aluminum	1220	1150	0.27	310	170	480	506,000	49,400	0.0976
Copper	1981	1911	0.11	210	88	298	314,000	101,000	0.323

Latent Heat of Fusion.—After a piece of metal has been raised to the fusion temperature, additional heat is required to transform it from the solid to the liquid state without further increase in temperature. This is called the latent heat of fusion and is usually expressed in Btu.'s per pound or calories per gram. It will be labeled H_1 in Btu.'s per pound.

Total Heat for Fusion (See Table 2)

Thus the total Btu.'s to fuse one pound of metal from room temperature

is $H_f = (T_f - T_a)h_s + H_1$ where T is the fusion temperature in degrees F., T_a the room temperature, h_s the average specific heat throughout the whole range up to fusion, $(T_f - T_a)h_s$ the Btu.'s to raise one pound from 70°F. to the fusion temperature, H_1 the latent heat of fusion in Btu.'s per pound, H_f the total heat for fusion $((T_f - T_a)h_s + H_1)$ in Btu.'s per pound, $J_{lb.}$ the joules per pound, J'' the joules per cubic inch and g the pounds, per cubic inch.

The basic data given in this table are the best available at this time, but should not be assumed as exact, since their determination is very difficult, and there are still differences between authorities. Moreover, in some cases there are differences due to variables other than those of chemical composition.

The latent heats of fusion for the three types of steel covered were not available. The table assumes them to be the same as for iron which is certainly on the high side for the steels.

Thermal Expansion

Since one of the most troublesome and most difficult problems connected with welding is that due to the expansion and contraction of the metal during heating and cooling, the coefficient of expansion or contraction is a vital thermal constant. This is given as K_e in Table 1 for the same metals thus far considered, and in inches per inch per degree F. It varies with the temperature, but accurate values for all temperatures are not available.

Thus, if a bar of mild steel L inches long has its temperature raised by T°F., its increase in length will be K_eLT. If $L = 10$ in., $T = 1000$°F., and the average value of K_e throughout this temperature range is 8×10^{-6} the expansion will be 0.08 in.

If the bar is restrained from expansion, the resulting compression stress will be K_eTE where E is the modulus of elasticity. Taking E at 30×10^6 the stress in this case would be 240,000 psi., provided that this were within the elastic range, which is not the case, since the compression yield point of this steel is only about 45,000 psi. In other words, the bar will be upset and permanently deformed by plastic flow.

If, on the other hand, this bar be allowed to cool through the same temperature range, but prevented from contracting by rigid restraint, it will be stretched far beyond the tension yield point, which is about 40,000 psi.

Thus the stress set up by heating or cooling under rigid restraint, is K_eE psi. per degree F., which is, in the case of steel, about 240 psi. per degree F.. averaged over this high temperature range, or about 200 psi. per degree F. in the low range. In the case of 18–8 stainless steel this will be 330 psi, per degree F. in the low range and in the case of aluminum 123 psi. per degree F. in the low range, E being only 10×10^6 in this case.

These are significant figures, since nearly every weld zone cools under partial restraint. In fact both design and welding sequence should be such as to reduce this restraint to the lowest point possible.

Surface Dissipation of Heat

When a surface is hotter than the surrounding air, heat is dissipated from

it by both radiation and convection, which follow different laws. These phenomena are quite complicated and dependent upon the nature, shape and orientation of the surface, as well as upon the surroundings, particularly the velocity of the air in contact with the surface.

Although this general subject will be treated more in detail in a later section of this chapter, certain approximate relations will be noted for use at this stage.

For moderate temperatures, 100–300°F., the total surface dissipation is nearly proportional to the excess of the surface temperature over the ambient, or surrounding air temperature.

If θ_s is the surface temperature, θ_a the ambient temperature and v the velocity of the air with respect to the surface, in feet per second, then the surface dissipation in watts per square inch is approximately

$$H'' = (\theta_s - \theta_a) \times 0.0044\sqrt{\frac{1.6 + v}{1.6}} = h\theta$$

where $\theta = \theta_s - \theta_a$ and h is the surface dissipation constant in watts per square inch per degree F.

This is only a rough average and is influenced by many factors.

Thermal Time Constant

Consider a body of metal receiving heat at a constant rate, with a resulting increase in temperature and in surface dissipation. It will be assumed that at any instant the temperature of the body is the same throughout.

Let $(\theta_s - \theta_a) = \theta$, the excess of surface temperature over the ambient.

Let C_b be the number of Btu.'s necessary to raise the temperature of the body by one degree F. This is sometimes called the heat capacity and is equal to the weight in pounds times the specific heat, or $C_b = wh_s$. It will be more convenient to express this in joules. C = joules per degree F. = 1055 C_b = 1055 wh_s.

Let p = the constant rate at which heat is being delivered to the body, expressed in watts. Then the joules delivered in t seconds will be pt.

Start with the body at ambient temperature, i.e., $\theta = 0$ when $t = 0$. If there were no loss by surface dissipation the temperature would rise steadily at a rate equal to $p \div C$ degrees F. per second or $d\theta/dt = p/C$. In fact, it does *start* to rise at that rate, but as soon as the temperature rises above the ambient, surface dissipation begins. If S is the surface area in square inches and θ the temperature rise at any time t, the rate of dissipation is $Sh\theta$, or $D\theta$, where D t= Sh is the dissipation constant for the body in question. Thus, at each instant a part of the heat is being dissipated and the remainder goes toward raising the temperature of the body. Consider the instant t and the corresponding temperature θ.

$$p = D\theta + C\frac{d\theta}{dt} \qquad (1)$$

where p is the constant rate of heat delivery, $D\theta$ is the rate of surface dissipation and $C(d\theta/dt)$ the rate of heat storage, all in watts. At the start when $t = 0$ and $\theta = 0$, $d\theta/dt = p/C$ which is the slope of the temperature-time curve at the origin (see Fig. 2). As θ increases, $d\theta/dt$ must decrease since p is constant, and there will always come a time when $d\theta/dt$ approaches zero; that is, θ will approach a final limiting value equal to p/D.

Equation (1) is the same as that for the build-up of an electric current in an inductive circuit, or the charging of a condenser through a resistance. The solution of (1) is

$$\theta = \frac{p}{D}[1 - \epsilon^{(-Dt/C)}] \qquad (2)$$

where ϵ is the base of Naperian logarithms (2.7183)

$$\text{When } t = \infty, \theta = \frac{p}{D} \text{ as indicated above}$$

$$\text{When } t = \frac{C}{D}, \theta = \frac{p}{D}\left(1 - \frac{1}{\epsilon}\right) = 0.632\,\frac{p}{D}$$

C/D is called the time constant T of the system and is the time required for the temperature to reach 0.632 of its final value, p/D. This is a very important constant, whether dealing with the heating up of an electric motor under constant load and losses, of an underground cable or of a spot-weld zone. In the case of the motor, T is of the order one hour, for the cable many hours and for a thin spot weld 0.01 sec. and much less in the case of thin aluminum.

Application to Spot Welding

In order to illustrate the nature of this thermal time constant point of view, consider making a spot weld between two sheets of 0.02-in. aluminum (Fig. 1).

Before considering the heat dissipation, it will be necessary to consider the rate of heat generation in the several parts of the weld zone due to the welding current. In any zone of electrical resistance r ohms, this is at any instant, $p = i^2r$ watts, where i is the current in amperes at the instant in question. But since the current is not constant in spot-welding practice, and the rate of heat delivery varies widely according to the shape of the current wave, it will be necessary to assume an equivalent constant current and constant rate of heat generation, which is $p_{avg.} = I^2r$ watts, where I is the root mean square (rms.) value of the current during the welding period. Although this neglects any effect of current wave shape, it will be sufficient for the present purpose. Other refinements of analysis, such as taking account of the distribution of current in the weld zone, have no place in this thermal analysis aimed only at a rough quantitative perspective.

The total electrical resistance between the electrodes may be divided into three parts: (1) r_i, the interface contact resistance; (2) r_m, the metallic resistance of the sheets; (3) $2r_e$, the electrode contact resistance.

The relative magnitudes of these vary widely with different metals, different surface conditions, different pressures and different temperatures. Without a detailed discussion of these complicated relations, certain quantitative values will be assumed and an effort made to present a fair picture of the thermal phenomena.

For the purpose of this crude picture, assume that at the start, r_e is equal to the resistance of 10 mils thickness of the metal being welded and that r_i is equal to the resistance of 20 mils of the same metal. Both of these contact resistances drop rapidly with the increase of temperature and r_i will obviously disappear as soon as fusion starts at the interface.

As the temperature of the metal rises, its resistivity increases at the rate of about $^1/_4$ of 1%* per degree F. As the initial rate of heat generation is

* This holds only for fairly pure metals. It is much less for high-resistivity alloys.

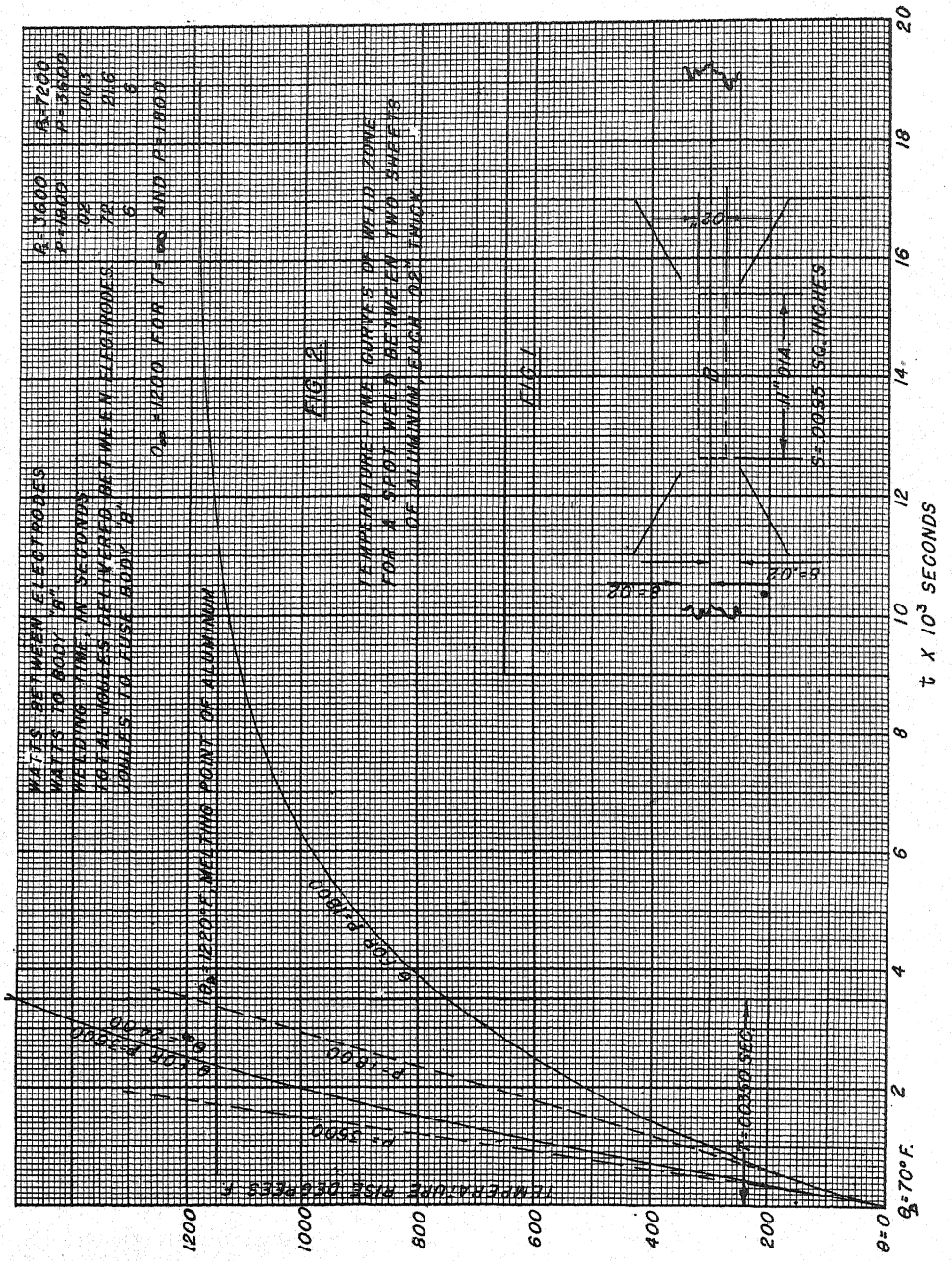


Fig. 1—Dimensional Sketch for Spot Weld Heat Flow Problem

Fig. 2—Temperature-Time Curves of Weld Zone for a Spot Weld Between Two Sheets of Aluminum, Each 0.02 In. Thick

a maximum at the interface, the temperature and resistivity will rise most rapidly in that zone. Thus, the initial high r_i will be replaced in some degree by a thin layer of hot high-resistivity metal which insures a maximum rate of heat generation in the interface zone.

In the meantime the relatively high initial rate of heat generation under the electrodes reduces the contact resistance r_e. Also the considerable heat developed at this point is carried off rapidly by the electrode material which is of high thermal conductivity. In fact, this is one of the fundamental requirements of the electrode material.

Thus, while the rate of heat generation under the electrodes is decreasing, that in the weld zone as a whole remains fairly constant or may even increase after a certain time. In any case, the weld zone has the highest temperature and heat flows therefrom in both directions to the much cooler electrodes. In fact, it is the magnitude of this heat flow and of the corresponding heat dissipation coefficient which is of primary interest in connection with this particular problem.

From the above crude picture it is obvious that anything approaching an exact analysis of the temperature distribution between electrodes throughout the welding period is impossible, not only because of the mathematical difficulties but also because of our lack of knowledge of both the electrical and thermal contact resistances of the interface and electrode contact zones. Any values assumed for these contact resistances are exceedingly crude and the quantitative results obtained therefrom should be accepted as indicating only the general relationships involved and the general nature of the phenomena. Even then they will be found to be very valuable from the practical point of view

In order to reduce this particular problem to the basis of the thermal time constant concept, it will be assumed that the "body" consists of the central half of the region between the electrodes, labeled B in Fig. 1. This is substantially the weld zone, fusion zone or nugget of the conventional spot weld. Assume, further, that heat is being delivered to this body at a constant rate and that as its temperature rises above that of the electrodes, heat will flow from the body through the cylindrical discs between the body and the electrodes and through the thermal contact resistances between the electrodes and the sheets. Although this thermal contact resistance varies with both pressure and temperature, it will be assumed that at normal pressure and at the average temperature, the thermal contact resistance is equal to the thermal resistance of 10 mils (0.01 in.) of the metal being welded. This is probably too high, particularly at high temperatures.

The volume of the body B is one-half of the weld zone, and is, in this case, $V = 0.00019$ cu. in., and its weight, $W = 0.00019 \times 0.0976 = 0.0000185$ lb. Since the average specific heat of aluminum is 0.27, the heat capacity constant is

$$C = 1055\ Wh_s = 0.00526 \text{ joule per degree F.}$$

It cannot be assumed that the electrodes remain at ambient temperature throughout the welding period, since a considerable amount of the heat is generated at the electrode contact surfaces by the electrical contact resistance r_e. This can be roughly accounted for by reducing D to one-half of what it would be with constant ambient electrode temperature. This is

equivalent to assuming that the electrode surface temperature rises half as rapidly as that of the body, which is a fair approximation for optimum welding conditions, although in some cases it may rise at a higher relative rate. However, one of the major requirements in spot welding is to keep this temperature below the danger point.

Thus the heat is dissipated from the body B, partly by conduction through the two thin discs between B and the electrodes, and partly by edgewise conduction into the surrounding sheets. The latter is usually much smaller than the former, and will be neglected in this very crude picture. Consider, then, the conduction to the electrodes. The thermal resistance of the two paths in parallel is

$$r_t = \tfrac{1}{2}\left(\frac{\rho_t''\delta}{2S} + r_{te}\right)$$

where ρ_t'' is the average thermal resistivity of the metal, δ the thickness of the sheets, S the area of the spot or section of the heat flow path, and r_{te} the thermal resistance between each electrode and the work. But we have assumed above that

$$r_{te} = \frac{0.01\rho_t''}{S}$$

Then,

$$r_t = \tfrac{1}{2}\rho_t''\left(\frac{0.5\delta + 0.01}{S}\right) \text{ thermal ohm inches}$$

or, since $\rho_{t\,\text{avg.}}'' = 0.32$, $S = 0.0095$ sq. in. and $\delta = 0.02$ in., therefore, $r_t = 0.337°$ F. per watt. Since $D_1 =$ watts per degrees F., then $D_1 = 1/r_t = 2.97$ watts conducted to the electrodes per degree F. difference in temperature between B and the electrode. But since it is assumed that the electrode temperature increases half as rapidly as the body B, the true D when expressed as watts per degree F. of temperature rise of the body itself will be $D = D_1 \div 2 = 1.48$, or, in order to simplify the numerical work, assume $D = 1.5$.

The resulting time constant will then be,

$$T = \frac{C}{D} = \frac{0.00526}{1.5} = 0.0035 \text{ sec.}$$

A little consideration will show that the separation of the whole weld zone into the body B and the two conducting discs is wholly artificial. Nevertheless B corresponds roughly to the familiar weld zone or nugget, and the maximum temperature gradient during much of the weld period is from B outward to the electrodes. However, this whole picture is based on conventional welding times, and would have to be altered to fit conditions far away therefrom.

In spite of all the crude approximations the resulting picture is helpful in acquiring a quantitative perspective of this problem, particularly when analyzed with regard to different materials and different thicknesses.

Figure 2 shows the temperature-time curves for this particular case and for two different rates of power input, p. It should be noted that p is the power delivered to the imaginary body which is only one-half the weld zone, and that the power delivered between the two electrodes (E_eI),

where E_e is the rms. volts between electrodes and I the rms. amperes, is about $2p$ in this case, more in some cases.

For thicker sheets, the thickness of the body B should remain the same (0.02 in.) for fast welds or increase slightly for slow welds.

It should also be noted that in making an actual weld the power delivered is not constant in either the a.c. method or in the stored energy method. Even thus both the time constant and the curves have real significance. In fact, this is just a starting point for a more thorough study of this whole problem, which is full of interest to the analytical mind, as well as of possibilities of practical value.

Although these curves and equations could be discussed at considerable length, only a few of the most significant relations will be noted.

1. If it were possible to measure the temperature at the interface and to plot it against time, the resulting curve would probably differ very materially from that shown in Fig. 2. In fact, at the start, and due to the high *initial* interface resistance, the temperature would rise more rapidly, and before the temperature of the remainder of the "body" had risen to any appreciable extent. However, the substantial equalization of temperature throughout the weld zone takes place very rapidly and the upper limit of that zone is determined by the ability of the electrodes to carry off the tremendous amount of heat conducted from the high-temperature weld zone through the intervening thermal resistance. In fact, it is altogether probable that in many cases of conventional welds, the electrode surface temperature rises considerably above that assumed above, namely one-half the temperature rise of the weld zone. In this case the heat dissipation coefficient D would be reduced from the value computed above. If this process goes too far, the result will be overheated electrodes, surface burning, serious indentation and unnecessary waste of energy. In fact, this often happens when the rate of heat input is too low and the welding time correspondingly long. Also in this case, the upper part of the temperature-time curve would rise above that shown in Fig. 2 owing to the decrease of the dissipation coefficient D.

2. Unless the power delivered to the weld zone is sufficient to complete the weld in three or four times T sec., it will not be completed at all except when accompanied by the undesirable features mentioned in paragraph (1).

3. If p is sufficient but t is too long, the same undesirable results will ensue; e.g., if the curve corresponding to $p = 1800$ is considered, the only results of a welding time greater than 0.02 sec. would be a greater thickness of the fusion zone and perhaps some of the undesirable results mentioned above. The quantitative part of this statement may not be exact, but it is qualitatively sound.

4. The following relations are approximately true. T is proportional to the thermal resistivity of the metal, to its specific heat and to the square of the thickness, δ. Two sheets only are assumed.

5. A comparison of the two curves of Fig. 2 shows that when p is doubled, the total joules required to complete the weld are reduced to about one-third, owing to the fact that the heat loss increases even more rapidly than the welding time. In fact, in the case of the slow weld ($p = 1800$) the total joules delivered between electrode tips is about 12 times that necessary to fuse the weld zone, and even this is less than that under con-

ventional welding technique. This heat loss decreases with increase of thermal resistivity and even more rapidly with increase of thickness.

This spot-welding problem has been discussed to some length, because it is an interesting example of the value of thermal arithmetic and provides a very useful aid to the visualization of the quantitative relations involved. It also indicates the value of more accurate quantitative experimental data which would make possible much closer approximations.

The analysis is wholly theoretical and makes no pretense at accuracy, although the general nature of the relations between the thermal properties of the material, the dimensions and the conclusions is correct. If it succeeds in stimulating the habit of more quantitative thinking, it will have served its purpose.

Transient Heat Flow

Although the above discussion of the thermal time constant deals in a very crude way with both space and time-temperature changes, it does not attempt to deal with point-to-point variations of temperature throughout the region under study, as is necessary in many welding problems. For example, it is often of vital importance to know with reasonable accuracy the rate of cooling, in degrees per second, in several parts of the weld zone, since both the microstructure and the residual stresses are critically related thereto.

For each variety of steel there is a critical rate of cooling throughout the transformation range or at different parts of that range, above which the microstructure and the physical properties are undesirable, and below which they are desirable, or at least acceptable. It is thus vitally important to be able to predict this rate of cooling for any given case, or to know how to modify the welding technique so as to keep the cooling rate within the desired limits. It depends upon the thermal properties of the material, upon the geometry of the set-up and upon the rate and location of the heat delivery.

The rate of cooling of a spot weld may be obtained roughly by a reversal of the analysis given above, but it will vary with the welding time and the spread of the heat during that time. It is an excellent problem to sharpen one's teeth on.

From a purely theoretical standpoint this determination of cooling rate in most cases is a very difficult job. This is one of those cases where the rational attack must be supplemented by experimental research. It is also one of those cases where this method of attack not only saves a large amount of time in experimental work, but also develops that thorough understanding of the quantitative connection between the several variables and the result, without which problems of this sort are just horrible headaches.

Methods of dealing quantitatively with such problems will be explained later on in this chapter.

THE GENERATION OF HEAT

Heat may be generated by electrical, chemical or mechanical means.

Of the electrical methods for the generation of heat there are two of great importance—the electric arc and electrical resistance. A third method of electrical heating, by induction, is often considered separately but is really a resistance method in which the current is induced in, rather than conducted to, the piece in which the heating takes place.

The Electric Arc

The electric arc is particularly suitable as a source of energy for welding, because the heat may be effectively concentrated. The temperature of the arc is difficult to measure but by means of the principle of the variation of the speed of a sound wave with temperature, Dr. Suits* has measured arc temperatures. The values which he has given are of the order of 6000°C. The temperature of the arc has frequently been assumed as the temperature of the boiling point of the electrode material, since the behavior of the arc appears very closely to consist of the boiling away (at least in part) of the electrode material at the surface. In the case of pure iron the best value of the boiling point is 3000°C. Carbon makes a good electrode material for arc heating since it has a high boiling point and passes directly from the solid to the vapor state, thus retaining its electrode form.

The exact temperature of the arc is really not important in the case of welding since the important considerations are that the arc should be capable of delivering large amounts of heat in concentrated form to the surface of the metal being welded and, in the case of a metal arc, that the temperature be such as to boil away the metal electrode rapidly. The power expended in an arc expressed in electrical units is a product of the current passing through the arc and the voltage drop across the arc. The voltage drop across the arc consists of fixed amounts at each terminal and a variable amount proportional to the length of the arc. A great deal of experimental work in measuring these various potentials has been done in the case of the carbon arc used for lighting purposes. Mrs. Ayrton† has shown that the voltage drop at the positive terminal of a carbon arc is much higher than the voltage drop at the negative terminal. This accounts for the greater heat developed at the positive terminal which is commonly experienced in the operation of carbon arcs. That the same conditions are also true in the case of a bare metallic electrode arc of low carbon steel explains the general use of polarity which makes the work positive and the electrode negative. This is due to the fact that the work usually has the larger mass and therefore requires the greater heat input for proper fusion. This polarity is referred to as straight polarity. The energies corresponding to the terminal drops of voltage are most effectively utilized, because they are delivered exactly where needed, to melt the electrode at one terminal of the arc and to melt the plate at the other terminal of the arc in preparation to receive the deposited molten metal. The energy corresponding to the voltage which varies with the arc length is also effective to a considerable degree, and permits some variation in the arc energy by manipulation of arc length. This variable voltage also serves as a measure of arc length, and thus as a basis for its automatic control. Although moderate lengthening of the arc increases the melting rate, it is also pos-

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* General Electric Research Laboratory.
† AYRTON, H., *The Electric Arc*, published by Electrician, London, 1902.

sible with most welding equipment to draw such a long arc as to decrease the melting of the base metal due to spreading of the arc energy over the surface.

Although the maximum heat is developed at the positive electrode in the case of a carbon or bare low carbon steel electrode, the reverse condition is true in some cases when the electrode is provided with a flux coating. Measurements are needed to check the terminal voltage in the case of electrodes with coating, in order to determine changes in these potential drops brought about by different constituents. With certain ionizing elements, obtained with coated electrodes, satisfactory operation of the arc requires that the electrode be connected to the positive terminal of the supply, and with this situation greater heat appears to be developed at the negative terminal. This is evident from the penetration secured with this polarity.

A clear distinction must be recognized between an electric arc and a resistance as a load on an electric power system. The usual power system is based upon the principle of applying a constant voltage. An electric arc is inherently unstable upon a constant potential system. This is due to the fact that as current increases, the voltage required to maintain the arc becomes less, whereas in the case of a resistance, an increase of current requires an increase of voltage. If an arc were connected directly to a constant potential circuit, the current would continue to increase indefinitely, or until the circuit protective device interrupted the current. To sum up the observations made thus far, it is evident that a drooping volt-ampere characteristic curve is unstable on a constant potential circuit, whereas the rising characteristic of a resistance results in a stable operating value of current.

In order to make an arc operate in a stable manner when connected to a constant potential circuit, it is necessary to place in series with the arc, a resistance of such magnitude that the combined characteristic is rising at the desired value of operating current. Figure 3 illustrates the relations. Curve A is the arc characteristic, Curve B is the voltage drop across the ballast resistance, placed in series for stabilizing and Curve C is the combined characteristic of the arc and resistance in series. If a voltage, E, of 70 volts, is now applied to the combined circuit, a current of 110 amp. will flow in the circuit. Since the energies used in the various parts of the circuit are proportional to the voltage drops in the figure, the efficiency in this case will be 25%. The minimum current for stable operation under these conditions is approximately 23 amp.

If it is desired to secure any particular value of operating current and at the same time place the stability limit close to the operating current, a graphical construction may be used to determine the magnitude of the applied voltage and of the necessary stabilizing resistance. For example, if it were desired to place the stability limit just 10% below the operating current or, in other words, at approximately 100 amp., we should draw a tangent to the arc characteristic at 100 amp. This tangent would intercept the voltage axis at 26 volts, which would then be the value of the applied voltage necessary to supply 100 amp. at the stability limit. The voltage to be consumed in the resistance would then be the difference between 26 volts and the arc voltage at 100 amp., which is 18 volts, or

8 volts. This voltage divided by the current of 100 amp. gives the value of the stabilizing resistance which will place the stability limit at 100 amp. If a parallel to the above-mentioned tangent were drawn through the point where the arc characteristic passes through a current flow of 110 amp., its intersection with the voltage axis would mark the voltage necessary to maintain the current of 110 amp., using the resistance value which would place the stability limit at 100 amp. This voltage would be only about

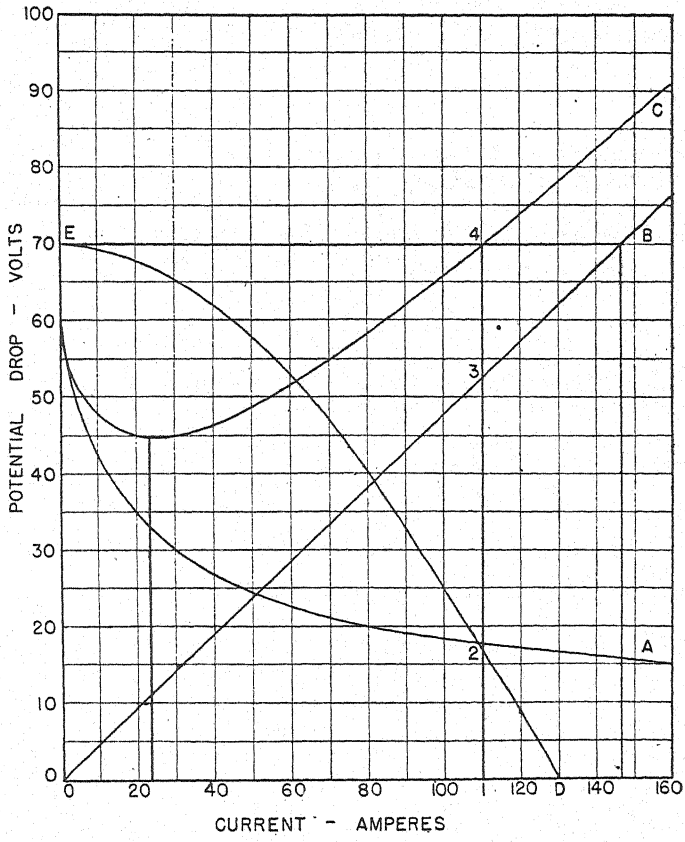


Fig. 3—Volt-Ampere Characteristic Curves for Electric Arc, Resistance and Variable Voltage Generator

one-half volt higher than the 26 volts required at the stability limit. The efficiency in this latter case would be approximately 68% for the welding operation. It would not be satisfactory to operate as close as this to the stability limit, since the arc characteristic varies materially with arc length so that a slight variation in arc length might easily raise the circuit voltage at the stability limit to a value higher than available. The reason for the above discussion, therefore, is to show the limitations toward which efficiency may possibly be extended, while at the same time practical

consideration may force the use of a circuit of lower efficiency. An open circuit voltage of 26.5 volts would be insufficient for satisfactory starting of the arc, as discussed below.

If, instead of a constant voltage source represented by the line *E-B* in Fig. 3, a variable voltage source having a characteristic such as *E-D* were available, stability would be achieved without the efficiency reduction occasioned by the energy-consuming resistance. The source characteristic, *E-D*, crosses the arc characteristic at point 2. This is a stable operating point since the source characteristic is drooping more rapidly than the circuit characteristic. In other words, *relatively*, the circuit characteristic is rising at this point.

In order to start an electric arc with any reasonable voltage, it is necessary to bring the electrodes in contact and then cause a gradual separation. This operation is referred to as "striking the arc." A minimum voltage satisfactory for striking a direct current arc is about 60 volts, although a somewhat higher voltage, for example 80, under many circumstances would be preferable, if no penalty were attached to its use. The operating voltage of a welding arc lies usually between 20 and 30 volts, although it may be as low as 15 or as high as 40 volts.

In order to strike an alternating current arc a higher voltage, by about 20 volts than the 60-volt minimum for direct current, is necessary. While 80 volts may be considered as a satisfactory minimum, 100 volts is preferable for striking an alternating current arc. In order to stabilize an alternating current arc, an inductive reactance is superior to a resistance from two viewpoints. First, the energy loss in a reactance is very slight in comparison to the loss in a stabilizing resistance, which latter may be two or three times the useful energy developed in the arc. Second, the reactance provides a better stabilizing effect than the same number of ohms of resistance, because of the lagging power factor produced. This is obvious when one realizes that an arc operating on alternating current becomes extinguished every time the current passes through its zero value, and must be re-established. In order to accomplish this the voltage must build up to a suitable value depending upon the conductance of the path, which is a function of the residual ionization. The ionization disappears rapidly after the arc is extinguished so that it is important for the voltage to build up as quickly as possible. With unity power factor the time required to build up the voltage will be a function of the frequency of the power supply. For this reason higher than normal frequencies are sometimes recommended as an aid to increased stability of alternating current arcs. However, with a lagging power factor the voltage has already built up in the proper direction to restart the arc by the time current passes through its zero value.

Because of the necessity for frequent restarting, the alternating current arc is inherently less stable than the direct current arc. If satisfactory operation is to be secured, factors other than the type of current, which are favorable to arc stability, must be present. These factors include covered electrodes, heavy current, high-frequency ignition superimposed on the power frequency and special constituents in the arc coating which tend to produce greater residual ionization. At least two of the above favorable factors must be present if satisfactory welding is to be had. Since the

advent of covered electrodes, alternating current welding has increased rapidly. Two important advantages are realized. First, the equipment is less expensive and of higher efficiency and lower maintenance cost than for direct current welding. Second, the magnetic disturbance of the arc is less troublesome with alternating than with direct current. Magnetic disturbance or "arc blow" often becomes a serious problem when welding heavy plates or into corners. The arc tends to blow out to the side, due to the effect of the magnetic field of current returning through the plate, upon the conducting stream of the arc. Other factors, besides the source of welding current, affect the stability of arcs. These are the presence of moving air currents in the vicinity of the arc and the presence of moisture upon the plates being welded.

Electrical Resistance

The electrical resistance method for the generation of heat has been discussed previously in this chapter in the example illustrating the application of the concept of thermal time constant to spot welding. As mentioned there, the resistances are body resistances and resistances at the various contacting surfaces. Body resistance is proportional to the resistivity of the material and the length of the current path, and inversely proportional to the area of the current path. Contact resistance is very much affected by surface condition; that is, by cleanliness and freedom from oxides or other chemical compounds, and by the roughness or smoothness of the surface. It also is a direct function of the resistivities of the materials in contact, and inversely proportional to the pressure. With given materials, of uniform surface condition, pressure becomes the major factor in the determination of contact resistance. The natural oxides, such as mill scale on steel, are of such non-uniform quality as to render uncertain the control of energy in resistance welding. It is therefore preferable to remove these oxides by pickling or to prevent their formation by cold rolling and controlled atmosphere annealing. It is evident that for materials of high resistivity, and for the heavier gages of material, the body resistance is of major importance and the contact resistance of relatively less importance. For high-conductivity materials, on the other hand, contact resistance is of the utmost importance. This results in the use of as light pressures as possible, which tends to permit cracking of welds in thin sheet, and porosity in welds made in heavier gage material. Differences in resistivity are reflected in rather widely different currents required to make the same size weld in various materials. In general the magnitudes of the resistances involved are small, of the order of less than a ten-thousandth of an ohm. Hence the currents are large, running into the thousands and tens of thousands of amperes. It is most convenient to supply such currents from alternating current systems, making use of transformers for stepping up the current.

It appears in the case of steel that contact resistance largely disappears during the first half cycle of the flow of current. It might seem therefore, that contact resistance would be of little importance. However, the greatly increased generation of heat during the first cycle, made possible by contact resistance, causes a significant increase in body resistance which rises with temperature. This boost in body resistance makes the remainder

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of the current more effective. The importance of contact resistance in materials of medium resistivity such as steel is borne out by the fact that higher pressures, which reduce contact resistance, necessitate higher welding currents.

Combustion of Gases

Of all the gases which may be made available for combustion, the burning of acetylene in oxygen results in the highest flame temperature. Another combination which results in a high temperature is the burning of hydrogen in oxygen. This flame has long been used for the welding of low melting point metals, such as aluminum. The temperature of the oxyacetylene flame is generally credited with being about 3200°C., which is ample for the welding of steel. The burning of acetylene in oxygen at the orifice of a torch takes place in two steps. The first of these is the burning of carbon to carbon monoxide, the hydrogen remaining unconsumed. This takes place in a small bluish white cone close to the torch in which the gases are mixed. It is this part of the reaction which gives rise to the heat which is most effective for welding. The burning of the carbon monoxide to carbon dioxide and of the hydrogen to water vapor takes place in a large blue flame which surrounds the welding operation but contributes only a preheating effect to the welding operation. The equations representing these two steps of combustion are as follows:

$$C_2H_2 + O_2 \longrightarrow 2CO + H_2$$

$$2CO + H_2 + 1^1/_2O_2 \longrightarrow CO_2 + H_2O$$

The first reaction above generates heat by the breaking up of acetylene as well as by the formation of carbon monoxide. The dissociation of each gram molecular weight of acetylene liberates 54.3 kg. cal. at 15°C. (254 Btu. per cubic foot of acetylene at 68°F. and 14.7 psi.). The combustion of the carbon to form two moles of carbon monoxide liberates 52.9 kg. $cal._{15}$ (247 Btu. per cubic foot of acetylene). The total heat supplied by the first reaction is therefore 107.2 kg. $cal._{15}$ (501 Btu. per cubic foot).

The second reaction liberates 68.4 kg. $cal._{15}$ (320 Btu. per cubic foot) by the burning of the hydrogen to water vapor. The combustion of each of the two moles of carbon monoxide provides 68.0 kg. $cal._{15}$ (318 Btu. per cubic foot), or an additional 136.0 kg. $cal._{15}$ (636 Btu. per cubic foot) for the reaction. The total heat supplied by the second reaction is therefore 204.4 kg. $cal._{15}$ (956 Btu. per cubic foot).

Adding the heat supplied by the two reactions gives the total heat of combustion for each mole of acetylene, which is 311.6 kg. cal. The above energy is equivalent to 1456 Btu. per cubic foot. The concentrated heat liberated by the first reaction in the small inner cone of the flame is 34.4% of the total heat, or 501 Btu. per cubic foot. The remainder of the heat is developed in the large brush-like outer envelope of the flame, and is effective for preheating. It is this heat which makes the great difference in cooling rate between acetylene gas and electric arc welding, which is one of the most characteristic differences between these processes. It is seen from the above reaction equations that one volume of oxygen is used in the first step of the combustion to burn one volume of acetylene. This oxygen must be supplied in the pure state. The one and one-half volumes of

oxygen required in the second step is picked up from the atmosphere. When just sufficient oxygen is supplied to burn the carbon to carbon monoxide, as indicated in the first step above, the resulting flame is said to be neutral. If less than enough oxygen is supplied to complete the combustion of the carbon, the flame is said to be carburizing, or an excess acetylene flame. This flame has certain uses in welding, and will be discussed in a later chapter. With more than enough oxygen for the first reaction above, the flame is oxidizing, which is detrimental for most welding.

The burning of hydrogen is a simple reaction with oxygen to form water vapor. The total heat of this reaction was given above as 68.4 kg. $cal._{15}$ per mole. This corresponds to 320 Btu. per cubic foot. If sufficient pure oxygen were supplied to completely burn all of the hydrogen, the flame temperature would be approximately 2900°C. However, this would not provide a protective outer envelope of reducing atmosphere, and consequently would be impractical. If only enough pure oxygen to burn half of the hydrogen is provided, the concentrated heat would be 34.2 kg. cal. per mole, or 160 Btu. per cubic foot. In this latter case the flame temperature would drop to a little over 2500°C. Comparing this temperature with 3200°C. for the acetylene flame, it is seen that with an oxy-hydrogen flame the temperature difference above the melting point of steel is only about 1000°C. in contrast to about 1700°C. for the oxyacetylene flame. The oxy-hydrogen process is obviously much slower for the welding of steel. It may be noted that by adjusting the amount of oxygen supplied, the relative proportions of concentrated heat and outer flame preheat may be varied. A similar control of the acetylene flame is not available, since any attempt to reduce the relative amount of the outer envelope heat results in an oxidizing flame, and a change in the other direction results in a carburizing flame.

Replacement of Metal in Compound—Thermit Welding

The molecular heat of formation of alumina is 399.0 kg. cal., a value greatly in excess of that of any other element. The heat of formation of iron oxide, Fe_3O_4, is 265.2 kg. cal. When metallic aluminum in the form of powder is mixed with powdered iron oxide, the reaction may be started by the burning of magnesium powder. The iron oxide is reduced at the expense of the aluminum, and the heat generated is sufficient to raise the temperature of the whole to about 3000°C., or about twice the melting point of steel. The reaction is

$$8Al + 3Fe_3O_4 \longrightarrow 9Fe + 4Al_2O_3 + 800.4 \text{ kg. cal.}$$

The excess heat in the steel forms a convenient method of welding heavy sections of iron or steel, and this is known as the Thermit process of welding. The fundamental advantage of this process is that the single contraction and slow cooling of the entire mass of weld metal in heavy sections result in a minimum of residual stress. When the section to be welded is restrained from contracting by the remainder of the structure, the single contraction may be compensated for by prior elastic deformation or thermal expansion of other portions of the structure, applied in such a way as to open the joint before welding.

Recombination of Molecules—Atomic Hydrogen Welding

The recombination of single atoms to form diatomic gas molecules results in the liberation of heat which is of importance in welding. Atomic hydrogen liberates 50.4 kg. cal. per mole (236 Btu. per cubic foot) in recombining to the stable molecular state. An additional 68.4 kg. cal. per mole (320 Btu. per cubic foot) is generated by burning in the air surrounding the weld of the molecular hydrogen to water vapor. This combustion effectively shields the molten weld metal from oxidation and the formation of nitrides. It also provides some preheat to the plate, and helps to retard cooling.

The dissociation of the gas may be brought about by passing it through an electric arc. When a plate of steel is placed in the path of the atomic hydrogen issuing from the arc, it serves to chill the gas sufficiently to favor immediate recombination at the surface. The heat is therefore delivered exactly where it is needed and the gas serves effectively to transfer energy from the arc to the surface.

Mechanical Methods

Mechanical methods for the generation of heat, like many chemical methods, have not found practical application as welding processes. This has been either because the generation of heat was insufficient in magnitude or in concentration. Friction and impact may under certain rare circumstances produce sufficient heat to make a weld. A steel tube may be revolved at high speed against a friction plate, until its temperature is above the critical and the metal is in a plastic condition. In this condition the end of the tube may be spun around and closed. However, the quality of the closure is under suspicion because of the possibility that the closure has resulted in trapped oxide in the joint.

The principal points with regard to any methods used for the development of welding heat are the intensity or concentration of the heat and the ability of the preparation or process to provide properly cleaned surfaces.

DISSIPATION OF HEAT

The dissipation of heat from the place at which it is generated is one of the factors controlling temperatures during the formation of a weld. Furthermore, after the generation of heat ceases, the manner in which cooling takes place has a profound influence on the properties of the weld and the adjacent metal. Heat tends to go to a region of lower temperature and of itself will only go along paths of decreasing temperature. The modes of heat transfer are commonly classified as conduction, convection and radiation.

1. Conduction

Problems involving the conduction of heat are divided into two general classes, constant and variable heat flow. In the former the heat flow is constant and the temperatures throughout the material are independent of

time. In variable heat flow, the heat flow and the temperatures in the material change with time. Practically all welding conduction problems are of the variable heat flow class. Mathematical expressions for the two classes of heat flow by conduction are given by Glazebrook,[1] Schack,[2] Bruce[3] and McAdams.[4]

(*a*) *Properties of Material Governing Heat Flow.*—The Fourier equations for heat flow in one direction are sufficient for a consideration of the properties of a material which govern the flow of heat. The equations are, for constant heat flow

$$q = -KA\frac{dT}{dx} \tag{1}$$

and for variable heat flow

$$\frac{\delta T}{\delta t} = \frac{K}{C\rho}\frac{\delta^2 T}{\delta x^2} \tag{2}$$

Table 3—Legend of Equation Symbols

Symbol	Description	Commonly Used Units
q	Quantity of heat flowing through the area A per unit time	Watts, cal./sec., Btu./hr.
A	Cross-sectional area through which the heat flows	Cm.^{2}, ft.^{2}
x	Distance in direction of heat flow	Cm., in.
T	Temperature	°F., °C.
t	Time	Sec., hr.
K	Thermal conductivity, the quantity of heat flowing per unit area, per unit temperature difference, per unit thickness, per unit time	Watts per cm.^{2} per °C. per cm.; cal. per sec. per cm.^{2} per °C. per cm.; Btu. per hr. per ft.^{2} per °F. per in.
C	Specific heat, the quantity of heat required to raise the temperature of unit mass one degree	Cal./gm. Btu./lb.
ρ	Density, the mass per unit volume	Gm./cm.^{3} Lb./ft.^{3}

In the steady state or constant heat flow the only property of a material governing heat flow is thermal conductivity (equation (1)). In variable heat flow, the instantaneous heat flow for a given point and temperature gradient is also governed solely by thermal conductivity. However, the temperature gradient changes with respect to both time and position, and hence other factors enter. The change in temperature with time is given by equation (2). Examination of this equation shows that a high thermal conductivity and low specific heat and density make for rapid heat flow. The term $K/C\rho$ is called the thermal diffusivity of a material.

(*b*) *Temperature Factors Governing Flow of Heat.*—A temperature difference between positions in any material is a prerequisite for heat flow, the amount of flow being related directly to it. The values of the properties of a material governing heat flow are dependent upon temperature.

The thermal conductivities of iron and low alloy steels decrease with increase in temperature. The thermal conductivity of a high alloy steel increases with increase in temperature. Thermal treatment may also affect thermal conductivity. Alloys of the same composition heat treated differently will have, in general, different thermal conductivities.

The specific heat of alpha iron increases with temperature up to the magnetic transformation. Between this and the gamma iron transformation a decrease with increase in temperature takes place. Above the

gamma iron transformation the specific heat again increases with temperature, the increase being much less than that for alpha iron.

The density of iron decreases with increase in temperature.

(*c*) *The Rate of Temperature Change with Time.*—The rate of temperature change with time during the cooling of a weld is important in order to obtain the proper transformation products and minimum residual stress. The change in temperature with time for heat flow in one direction and without losses to the surrounding medium is given by equation (2).

The cooling rate of welds has been presented by Henry and Claussen.[6] The reader is referred to this work for an understanding of the metallurgical importance of properly cooling a weld.

The cooling of casing welds has been presented by Hodell.[5] Volume and magnetic changes were observed and from the results the proper cooling rate obtained. A method of determining the rate of change of magnetic induction in the weld on cooling was described. On account of composition variation, not only in different steels but also in the same piece of casing steel, no tabulations were made which could be applied to a particular steel.

(*d*) *Heat Flow Problems.*—Rectangular parallellopipeds and cylinders are the shapes most frequently met with in problems involving constant heat flow. The equations for the two shapes are:

$$\text{Rectangular parallellopiped } q = KA\,\frac{\Delta T}{\Delta X} \tag{3}$$

$$\text{Cylinder or cylindrical shell } q = 2.73\,\frac{KL\Delta T}{\log_{10}(b/a)} \tag{4}$$

where q = heat flow per unit time (radially).
ΔX = thickness.
ΔT = temperature difference.
L = length of cylinder, in the same system of units as K is expressed.
a = inner diameter.
b = outer diameter.

The solution of problems involving variable heat flow are more difficult than for constant heat flow. The general equation for variable heat flow in three dimensions is

$$\frac{\delta T}{\delta t} = \frac{K}{C\rho}\left(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2}\right) \tag{5}$$

where x, y and z = distances along axes of a rectangular coordinate system.

The heating or cooling of a body by exterior means involves an additional term for the transfer of heat between its surroundings and the surface of the body. McAdams[4a] gives the Gurney-Lurie[7] charts by which solutions for this type of problem may be obtained. With such factors as thermal conductivity, specific heat, density and surface heat transfer coefficient known, the time of heating, the time required for a given point in the body to reach a given temperature and other quantities may be calculated for slabs, cylinders, spheres and semi-infinite solids.

In welding, the temperature at a given point and time or the rate of temperature change with time is of most interest. Bruce[3] has developed

equations for calculating the temperature of a weld for various welding conditions. Of particular interest is the treatment of the thermal distribution and temperature gradient in the arc welding of oil well casing. In this problem Bruce developed an equation which permits the calculation of the temperature of any point at any time after the welding operators break arc on a thin wall casing. He also considers the effect of various numbers of welding operators on the thermal problem.

Other problems treated by Bruce are the welding of cylindrical tubing along an element of the cylinder, narrow flat plates, narrow flat plates with a backing plate and a bell and spigot pipe joint. In each case the temperature equation is given.

(*e*) *Tables, Thermal Conductivity, Specific Heat and Density Including Variations with Temperature.*—Table 4 gives the thermal conductivity, specific heat and density of iron as obtained from the indicated sources.

Table 4—The Thermal Conductivity, Specific Heat and Density of Iron at Various Temperatures

Temperature, °C.	Thermal Conductivity,* Cal./Cm.²/Cm./Sec./°C.	Specific Heat,† Cal./Gm.	Density,† Gm./Cm.³
		Alpha Iron	
0	0.173‡	0.104	7.87
200	0.145	0.128	7.82
400	0.117	0.151	7.74
600	0.091‡	0.188	7.67
800	....	0.210	..
		Gamma Iron	
1000	....	0.162	..
1200	....	0.165	..
1400	....	0.169	7.42

* Shelton, S. M., "Basic Open Hearth Iron," *Bureau Standards Journal Research*, 12, 447.
† *American Society Metals Handbook*, pp. 426, 430 and 431 (1939).
‡ Extrapolated values.

Table 5 gives the thermal conductivities of some of the commonly used

Table 5—The Thermal Conductivities of Some Commonly Used Metals

Metal No.	Material (See Table 6 for Compositions)	Thermal Conductivity, Cal./Cm.²/Sec./°C./Cm				
		100°C.	200°C.	300°C.	400°C.	500°C.
1	Basic open hearth iron	0.159	0.145	0.131	0.117	0.104
2	Low carbon steel	0.193	0.165	0.140	0.123	0.109
3	Medium carbon steel	0.180	0.154	0.125	0.105	0.091
4	High carbon steel	0.162	0.132	0.109	0.085	0.075
5	18–8 stainless steel	0.037	0.041	0.045	0.048	0.052
6	Chromium steel	0.060	0.062	0.064	0.066	...
7	High chromium steel	0.050	0.052	0.055	0.057	0.058
8	Copper	0.923*	...	...	...	...
9	High nickel copper	0.066	...	...	0.087	...
10	Nickel bronze	0.087	...	...	0.120	...
11	Nickel aluminum bronze	0.082	...	...	0.126	...
12	Aluminum bronze	0.144	...	...	0.197	...
13	Aluminum	0.52*	...	...	...	...
14	Aluminum-copper-silicon	0.452†	0.460	...	...	...

* Value for room temperature.
† Value for 25°C.

metals which are encountered in welding practice. The compositions of the metals are given in Table 6.

Table 6—The Compositions of the Metals Given in Table 5

Metal No.	Composition											Reference
	Fe	Cu	Al	C	Mg	Ni	Cr	Mn	Si	Sn	Zn	
1	Bal.	...	...	0.02	...	...	...	0.03	..	..	..	(1)
2	Bal.	...	...	0.065	...	...	...	0.40	..	..	..	(2)
3	Bal.	...	...	0.29	...	...	...	0.84	..	..	..	(2)
4	Bal.	...	...	0.52	...	...	...	0.63	..	..	..	(2)
5	Bal.	...	...	0.24	...	8.96	19.6	0.37	..	..	..	(1)
6	Bal.	...	...	0.07	...	0.23	12.00	0.09	0.09	..	..	(1)
7	Bal.	...	...	0.10	...	0.18	26.00	0.40	0.45	..	..	(1)
8	...	100	...	...	...	...	...	..	..	..	..	(3)
9	1.79	29.46	...	0.21	...	67.34	...	1.11	0.07	..	..	(4)
10	...	73.28	...	...	...	16.06	...	...	..	9.67	0.99	(4)
11	2.96	81.69	9.77	...	...	3.71	...	1.95	..	..	..	(4)
12	Trace	89.56	8.66	...	...	...	...	1.75	..	..	..	(4)
13	...	...	100	...	...	...	...	..	..	..	..	(3)
14	0.73	4.39	Bal.	...	...	...	...	..	0.66	..	..	(5)

References:

(1) Shelton, S. M., *U. S. Bureau Standards Journal Research*, 12, 441 (1934).
(2) Esser, H., and Others, *Archiv Eissenhuttenwessen*, 11, 619 (1937–38).
(3) *American Society Metals Handbook*, p. 79 (1939).
(4) Donaldson, J. W., *Journal Institute of Metals*, 65, 139 (1939).
(5) Smith, C. S., and Others, *Metals Technology*, 4, T. P. 783 (1937).

2. Convection

(*a*) *Circumstances Favorable to Convection.*—Convection is the term applied when heat is transferred by the movement, as a whole, of the substances being heated or cooled and may be natural, as rising air adjacent to a heated wall, or forced, as mechanically blowing air over the wall. It is practically impossible to separate heat flow by conduction and convection when heat flows from a surface to an adjacent medium. Langmuir[8] developed the film theory for heat transfer of this type. He assumed that near the surface laminar flow would be present and that the temperature gradient through this region would be almost linear. Beyond this region the flow would be turbulent and the temperature would be that of the main part of the medium. Kennard[9] conducted experiments which showed that the temperature of the medium decreases at first almost linearly with distance but as the distance increases the temperature asymptotically approaches the temperature of the main body. The temperature difference between the surface and the medium and the velocity with which the medium passes over the surface are factors regulating this type of heat flow. The greater either of these factors is, the greater will be the heat flow.

In heat transfer by natural convection the position of the hot surface with regard to the establishment of convection currents is important. A horizontal surface with heat loss downward will not lose as much heat by convection as if the heat flow were upward from the surface.

(*b*) *Heat Dissipation Equation.*—There is no general equation for heat transfer by convection. Glazebrook[1] and Schack[2] give a number of equa-

tions, each being applicable only for special conditions. In the case of heat transfer by natural convection, Glazebrook[1a] shows that a number of investigators have found the heat loss to be proportional to the 5/4 power of the temperature difference between the surface and the medium.

$$q = B(\Delta T)^{5/4} \tag{7}$$

where q = quantity of heat flow per unit area per unit time.
ΔT = temperature difference
B = constant depending upon existing conditions.

For forced convection Glazebrook[1] gives the heat loss by convection as depending on $\sqrt{V}$, for small wires, and as proportional to V for large bodies, V being the velocity of the medium.

3. Radiation

(*a*) *Laws Governing the Radiation of Heat.*—In heat transfer by radiation the terms black body and emissivity are frequently used. A black body is one which absorbs and emits all radiation of all wave lengths falling upon it as a result of temperature and reflects none. Emissivity is the ratio of the radiant energy emitted per unit time and area by a body to that emitted by a black body at the same temperature. The emissivity used in heat transfer is called total emissivity distinguishing it from spectral emissivity used in dealing with monochromatic radiation.

The fundamental law for heat loss by total radiation is the result of both experimental and theoretical work. This law known as the Stefan-Boltzmann[2a] law is

$$q = CA(T_1^4 - T_2^4) \tag{8}$$

where q = cal./sec.
A = area cm^2.
T_1 = temperature (°abs.) of the radiating surface. (Kelvin Scale)
T_2 = temperature (°abs.) of the irradiated surface.
C = constant = 1.37×10^{-12} cal./cm.^{2}/sec./°C abs.^{4}

In practice most surfaces do not radiate like a black body, hence their emissivity is less than unity. By use of Kirchhoffs[2b] radiation law and the Stafen-Boltzmann equation (8) the total radiation loss from a non-black body is

$$q = CA\epsilon\,(T_1^4 - T_2^4) \tag{9}$$

where ϵ = emissivity.

If the heat flow takes place between two parallel surfaces the emissivity of equation (9) is

$$\epsilon = \frac{\epsilon_1\epsilon_2}{\epsilon_1 + \epsilon_2 - \epsilon_1\epsilon_2} \tag{10}$$

where ϵ_1 = emissivity of one surface.
ϵ_2 = emissivity of the other surface.

The heat loss by total radiation as given by equation (9) is of interest in most practical cases. By use of Lambert's[2c] radiation law and equation (9) the radiation loss in any given direction is

$$q_d = \frac{CA\epsilon(T_1^4 - T_2^4)}{\pi} \cos \phi \qquad (11)$$

where q_d = radiation loss in the direction making an angle ϕ with the normal to the radiating surface.

Equation 11 does not hold for polished metal surfaces as these generally show greater radiation in an oblique direction than perpendicular to the surface.

(*b*) *Surface Conditions and Coefficients.*—The emissivity of a body results in part from surface conditions. In general for a given metal the more highly polished the surface is the lower will be its emissivity. The total emissivities of some metals are given in Table 7.

Table 7—The Total Emissivity of Some Metals*

Metal	Surface Condition	Temperature, °C.	Total Emissivity
Iron	Unoxidized	100	0.05
Iron	Oxidized	100	0.74
		500	0.84
		1200	0.89
Iron	Rusted	25	0.65
Steel	Unoxidized	100	0.08
Steel	Oxidized	25	0.80
		200	0.79
		600	0.79
55Fe-20Ni-25Cr	Oxidized	200	0.90
		500	0.97
Copper	Unoxidized	100	0.02
Copper	Oxidized	200	0.6
Monel	Oxidized	200	0.43
		600	0.43
Aluminum	Unoxidized	25	0.022
		100	0.028
		500	0.060
Aluminum	Oxidized	200	0.11
		600	0.19

* Values taken from *Temperature—Its Measurement and Control in Science and Industry*, Reinhold, 1941, pp. 1314–1315. Values given for oxidized surfaces are uncertain by 10–30%.

4. Relative Importance of Conduction, Convection and Radiation

In the dissipation of heat from a completed weld, the thermal conductivity, or better the thermal diffusivity, which is equal to the thermal conductivity divided by the product of the specific heat and density, is the factor besides temperature gradient governing the flow of heat in the metal to the surface. Convection and radiation are the means of transferring the heat from the surface to the surrounding medium. The greater the temperature difference between the weld and the medium, the greater will be these heat losses per unit time provided sufficient quantity of heat from within the weld reaches the surface in the same time.

Jensen[10] gives some curves showing the relative loss of heat by convection and radiation. For very calm air the heat loss by radiation is greater

than for convection for all temperatures of the weld. When air is blowing over the weld with a velocity of 10 meters per second the heat loss by radiation and convection are about equal at approximately 500 °C. At higher temperatures the heat loss by radiation is greater and the difference in heat loss by radiation and convection increases rapidly with temperature. Below approximately 500 °C. the heat loss by convection is greater. The curves show in this case that at 100 °C. the heat loss by convection is about five times that lost by radiation.

(*a*) *Thin Sections.*—In a thin section the thickness of metal through which the heat is conveyed to the surface is small and hence the resistance to heat flow to the surface is small. The ratio of surface area through which heat is lost to the volume of metal present is relatively large. The heat loss from this type of welded section is governed principally by the factors influencing loss by convection and radiation.

(*b*) *Heavy Sections.*—Heat from within a heavy section has to go farther to reach the surface than does the heat from within a light section. The rate at which it reaches the surface depends upon the thermal diffusivity of the metal and the temperature gradient between the surface and the interior of the metal. The rate of heat dissipation from this type of welded section depends not only upon convection and radiation but also upon the thermal properties of the metal. Protection may or may not be required during the cooling of such a weld, depending upon its metallurgical characteristics.

In almost all types of welding the most important factor governing the dissipation of heat from the weld area is conduction. This is due to the steep thermal gradients adjacent to the weld which result from the localized application of heat. This is very different from the case of an entire metallic body heated to a uniform high temperature. The effect of rapid cooling by conduction is accentuated in the case of heavy plates welded with small electrodes, due to the relatively large path through which heat may escape from the weld area and the large heat reservoir provided by the heavy plate.

(*c*) *Thermal Conductivity.*—The thermal conductivity or better the thermal diffusivity of the metal in a weld is a factor along with temperature gradient and the geometry of the metal, which determines the rate of heat flow from the interior of the metal to the surface. Metals with the higher thermal conductivities generally have higher diffusivities. The thermal conductivities of iron, aluminum and copper are, respectively, 0.19, 0.52 and 0.92 and in the same order thermal diffusivities are 0.22, 0.85 and 1.12, both properties being expressed in cgs. units. With the same conditions of temperature gradient, geometry and ability to lose heat to the surrounding medium the metal with the higher thermal diffusivity will dissipate heat from a weld at a greater rate than a metal with a lower thermal diffusivity.

5. Reversible Heat

During the heating of a metal to its fusion temperature, some of the heat is dissipated as described above. Additional heat must also be supplied to bring about transformation and actual fusion. This is known as reversible heat, since it is not lost during the heating operation, but only

changed to another form, from which it will be restored upon subsequent cooling.

One gram of iron at 25 °C. requires approximately 316 calories for melting. Approximately 70 calories of this required heat are in the form of reversible heat, that is, heats of transformation and fusion. Thus in melting iron for welding about 22% of the heat required is in the form of reversible heat. The heat of transformation[11] at the A_3 point is 3.63 calories per gram and at the A_4 point 1.7 calories per gram. The heat of fusion[11] is given as a rounded figure of 65 calories per gram.

Similar data for steel are not available excepting values for the A_1 transformation in a eutectoid steel. Epstein[12] gives 15.9 calories per gram for the heat transformation at the A_1 point. Considering this value and the heat of fusion approximately 25% of the heat required in melting steel for welding is in the form of reversible heat.

MECHANICAL PROBLEMS

Expansion and Contraction

The most common and widely known effect of temperature upon metals is expansion on heating and contraction on cooling in all three directions: length, width and thickness. As an example, Curve A, Fig. 4, represents the increase of length, in per cent of initial length, of a mild steel, grade

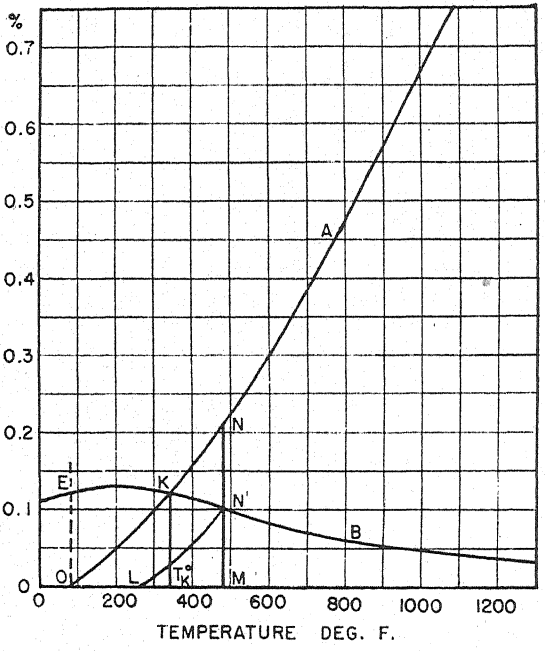


Fig. 4—Thermal Elongation and Elastic Limit Curves as a Function of Temperature for Plain Low Carbon Steel, S.A.E. 1020

S.A.E. 1020, when heated above the room temperature. The increase is nearly linear and amounts to almost 1% at 1200°F.

Since welding is a local operation, the extent to which the metal will be heated and thereafter cooled will be very limited. Consequently there will be little possibility of free expansion and contraction. *Because of this a state of constraint will be originated in welded articles,* and this constraint is expressed most conveniently in terms of stresses. Since there is no external load applied to the object, these stresses may be conveniently called "locked-up."* Locked-up stresses may or may not disappear when room temperature is restored. Stresses produced during local heating will be referred to as *thermal stresses.* Stresses which remain after the weld has cooled to room temperature will be called *residual stresses.* From the point of view of welding technique the residual stresses are the more important.

Factors Favoring the Production of Residual Stresses

As stated previously, residual stresses may or may not occur when the heated article has been brought back to its initial temperature. Thus, heat input alone is not sufficient to promote their existence. In fact, residual stresses may be created without any heating at all being involved in the process. For example, residual stresses may readily result from any machining or forming operation.

It has become common knowledge that rolling sets up important residual stresses in large I-beams. It has also been pointed out repeatedly that cold working is responsible for creation of residual stresses in deep drawn brass tubes. Furthermore, there is ample evidence to the effect that milling and grinding may leave the surface of the metal under considerable compressive stress.

While it is not the purpose of this HANDBOOK to deal with processes other than welding, it may be said that, as a general rule, the occurrence of residual stresses is essentially connected with *some permanent set* taking place during the operation.

With respect to the residual stresses set up by heating the following factors are essential:

1. Existence of a definite thermal expansion.
2. Non-uniform temperature distribution.
3. Local permanent (plastic) deformation.

All three conditions are necessary to promote residual stress, for,

1. No constraint and consequently no residual stress is possible without thermal expansion. That is why quartz, whose thermal coefficient is practically zero, may undergo safely any drastic change in temperature despite its high brittleness;
2. If a body is heated and cooled uniformly, there can be no reciprocal constraint due to thermal expansion and consequently no residual stress;
3. If the article suffers no permanent (plastic) strain during the whole thermal cycle, then the strain, being only elastic, must disappear when the initial temperature is restored.

According to this principle, a material which remains entirely elastic,

* The word "internal" is also applied to these stresses. This word seems inadequate in so far as all stresses, even those resulting from external load, are internal.

up to the breaking point, will never retain any residual stress. It may eventually fail, if the heat input imposes upon it a stress which exceeds the ultimate strength. Under usual working conditions mild steel and most of the structural metals exhibit considerable plastic yield before breaking, and this is exemplified by the usual stress-strain diagram of mild steel S.A.E. 1020, in tension, Fig. 5.

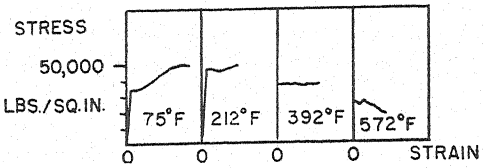


Fig. 5—Stress-Strain Diagrams for Plain Low Carbon Steel, S.A.E. 1020, at Various Temperatures

At room temperature the strain remains purely elastic only up to about 0.1% elongation. When the stress exceeds only slightly the elastic limit, the strain suddenly becomes plastic and, with little or no increase in stress, may increase to more than ten times its value just below the elastic limit.

A similar trend is exhibited at higher temperatures, as shown in Fig. 5, but the maximum elastic strain is not the same; at first it increases with temperature up to 350°F., then it decreases rapidly. Above 900°F. there is no longer a definite elastic limit because of creep phenomena, and it is doubtful whether there can be any elastic strain at all above 1200°F. If the values of the maximum elastic strain are replotted in the diagram, Fig. 4, the Curve B is obtained. It is seen that this curve intersects the Curve A at the point K which corresponds to the temperature $T_K = 340°F$. Below this temperature the thermal expansion is smaller than the strain at the elastic limit; above this temperature it is greater than the elastic strain.

The exact location of the temperature T_K is important for the occurrence of residual stress. For, as will be seen later, no residual stress can ever occur if the highest temperature during the thermal cycle lies below the temperature T_K. Nor can any possible change in shape or dimension take place after the cooling is completed, *provided the material was stress-free at the start.* Unfortunately, not only is the temperature T_K different for different materials, but there is good reason to believe that it may change with the state of stress imposed upon the object. Although more experimental work is needed to secure reliable information on this point, it may be assumed for the present that Curve B is valid when the specimen is submitted to compression instead of tension. Of course, the values will be negative instead of positive.

With this in mind, it will be shown that, if all of the three previously mentioned conditions are present, residual stress may occur due to heat input.

For the sake of simplicity, let us consider the assembly represented in Fig. 6. It consists of a bar, A, inserted into a frame. We shall assume

that the assembly is of mild steel, S.A.E. 1020. Upon heating, the bar A would expand according to the Curve A, Fig. 4, if removed from the frame, and this fulfills the condition 1. Furthermore, if the bar A alone is heated while kept inserted in the frame, condition 2 will be also fulfilled.

Now, it will be assumed for the sake of simplicity that the frame is rigid enough to prevent any deformation of the bar. Thus, the thermal expansion, ϵ_t, will have to be cancelled by a mechanical compression, $-\epsilon_m$ resulting from the reaction of the frame. We may thus write

$$\epsilon_t - \epsilon_m = 0 \qquad (12)$$

From the diagrams, Fig. 4, it follows that up to the temperature T_K the

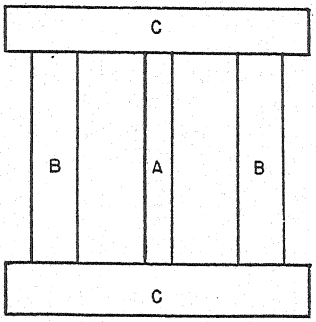


Fig. 6—Rigid Frame Diagram for Illustrating the Effects of Thermal Elongation and Plastic Deformation on Production of Residual Stresses

mechanical strain ϵ_m will be purely *elastic*. Therefore, if from T_K or any lower temperature, the bar is cooled back to room temperature, no residual strain will be left in the assembly. But above the temperature T_K, say at M, the thermal expansion $\epsilon_t = MN$, is greater than the available maximum elastic compression, $-\epsilon_e = N'M$. Consequently, the bar A must undergo a plastic deformation, $\epsilon_p = NN'$, of sufficient amount to cancel the thermal expansion ϵ_t. In other words,

$$\epsilon_t - \epsilon_e - \epsilon_p = 0 \qquad (13)$$

The existence of plastic flow "ϵ_p" fulfills the third condition, and it is easy to see that now the bar A will retain some residual tension when cooled down to room temperature. For, if left free, the bar would become shorter by the amount NN', and to prevent the contraction the frame must submit the bar to a strain of opposite sign; i.e., to an elongation equal to NN'. If NN' is smaller than the elastic strain, OE at room temperature, the residual stress S_r will be equal to $NN' \times E$, where E is the modulus of elasticity.

If NN' is greater than the maximum elastic strain OE at room temperature, a part of the residual strain will become plastic and the residual stress will be practically equal to the elastic limit.

Similar conditions prevail in welding. Any welding process involves definite expansion, non-uniform temperature distribution and local plastic flow. Two butt-welded plates exert upon the weld the same action as the frame upon the bar A by preventing the weld from shrinking longitu-

dinally. Hence, residual stress is almost unavoidable in welding. However, the reciprocal influence between the heat-affected and non-affected part of the welded article is not exactly that of a heated bar inserted into a rigid frame. First, this mutual influence is exerted not only in one direction but in all three directions. Furthermore, unlike the rigid assembly the welded object as a whole may undergo some general residual distortion, and it is of interest to know how this last modification would affect the residual stress.

To make it clearer let it be assumed that the assembly in Fig. 6 is no longer rigid and that each of the two columns has the same cross-section as the bar A, equal to one square inch. Then the bar will be only partially restrained from contracting, and the amount of contraction which will actually occur will place the columns in compression. If the yokes, CC, are rigid, the contraction must be the same for the bar and columns. There must also be an equilibrium of stresses.

From these two conditions the magnitude of the stresses and the amount of plastic flow of the bar may be computed if the amount of general contraction is known.

As an example let us assume that the amount of contraction which places the columns in compression is -0.03%. Then each of the columns is submitted to a residual stress.

$$S_c = \frac{-0.03}{100} \times E$$

where E is the modulus of elasticity equal to 30,000,000 psi. Hence

$$S_c = -9000 \text{ psi.}$$

The total compression upon the columns will be found as a product of S_c and the cross-section of the column (2 sq. in.) = 18,000 lb. This *compression* is balanced by an equal *tension* acting upon the bar.

Hence the residual tension in the bar (cross-section = 1 sq. in.) = +18,000 psi., and the corresponding strain = 18,000/30,000,000 = $+0.06\%$.

Because of the tension strain, the bar has been unable to contract more than 0.03% assumed previously.

Thus, the total contraction which would have occurred, if the bar had been able to shrink freely, is:

$$0.03\% + 0.06\% = 0.09\%$$

This total contraction represents the plastic flow undergone by the bar during the heating cycle.

The consideration of this simple case suggests that, if the amount of shrinkage undergone by the object during welding is known, it is possible to compute the amount of residual stress on the basis of the law of equilibrium of forces, and also to determine the amount of plastic flow involved in welding. Conversely, the knowledge of the amount and extent of plastic deformation in welded objects should permit the computation of the amount of shrinkage and residual stress on the basis of the law of continuity of deformation and equilibrium of forces.

Now, consideration of Fig. 4 suggests that the amount of plastic deformation is dependent upon the maximum temperature reached during heating.

In this way the whole problem of residual stresses would be based really upon the knowledge of heat distribution during welding.

An attempt to derive the distribution of residual stresses from the distribution of temperature during welding has shown that in simple cases a good approximation has been obtained, at least in points which were located not too close to the weld. It is doubtful whether this procedure would yield more than a qualitative picture in more complicated cases.* The plastic behavior of the material under two- and three-dimensional state of stress, such as is encountered in actual welding, is far from being known, and without this knowledge the relation between stress and strain can be merely a matter of speculation.

For example, sometimes it has been stated that the greater the distortion the smaller are the residual stresses. This statement is mostly based upon consideration of elementary cases like that offered by the assembly of Fig. 6. It will be realized that, if this assembly undergoes no shrinkage whatsoever, the whole plastic deformation of the bar, -0.09%, in the previous example, must be cancelled by the elastic strain, and this will result in an increase of the residual stress from 18,000 to 27,000 psi. Actually it has been found in welding that greater distortion was not necessarily combined with a lower residual stress, and this seems to be a warning against too hasty generalization.

Rigidity

Contrary to common belief, an increase of rigidity from a one- to a two-dimensional case does not appear to increase appreciably the value of residual stress in the direction parallel to welding. Nor is the plastic flow impeded in this direction to any extent by the additional residual stress in the transverse direction.

Nothing is known definitely of the behavior of weldments when the rigidity becomes a three-dimensional one. However, it may be suspected that the ability to flow plastically is greatly reduced, and this has to be borne in mind when considering the importance of residual stress.

Importance of Residual Stresses

Many factors determine whether residual stresses are important in service. This subject is treated in Chapter 32B. Only one or two points will be emphasized here. The importance of residual stresses is largely dependent on whether or not the structure has the possibility of plastic flow under the combined effect of residual and working stress.

If the combined effect of the residual and working stress acts primarily in only one direction (one-dimensional state of stress), plastic flow will start in most of the structural materials, and there is strong evidence that the residual stresses will be ironed out long before the ultimate stress is reached.

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* It may, however, be useful in predicting the sign and the probable location of maximum residual tension. As a rule, the part which is the last to cool down to the room temperature will also be the one submitted to the highest residual tension.

Thus, the ultimate resistance of the material will not be impaired by the residual stress.

On the other hand, if the combined effect of residual and working stress results in an equal constraint in all three directions (three-dimensional state of stress), the plastic flow may become very limited, and residual stress quite harmful. At present this is at best only a good guess, since experimental difficulties preclude any direct confirmation.

Control of Residual Stresses

The amount of residual stresses which may be present as a result of welding may be controlled by proper attention to the design of the structure, the sequence of welding and by mechanical or thermal distortion of the structure before welding to allow for weld shrinkage. The basic principle underlying all methods of control consists in providing facilities to the heated area for unrestricted shrinkage, particularly within the elastic range. The sequence of welding should secure, as far as possible, freedom from shrinkage.

Design of Welding.—In accordance with the above basic principle welds should be located at parts which possess the smallest rigidity. As a rule, one should avoid placing welded joints at fillets and should also avoid combining them with any shape or dimensional change, Fig. 7-A, B. Nor

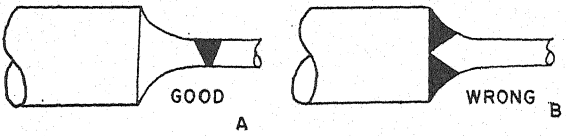


Fig. 7—Diagram Illustrating the Principle of Avoiding the Positioning of Welds in Highly Stressed Structures at Points of Important Change of Section

should welds be accumulated at the same spot, as this will tend to develop a two- or three-dimensional state of residual stress.

Proper design is essential not as a means of suppressing the residual stresses, but rather as a means of decreasing their dimensional complexity.

Mechanical Control.—The principle underlying this control is best explained by the following example:

Suppose the central column of the assembly, represented by Fig. 8, is broken and has to be repaired by welding. The amount of axial shrinkage involved by welding is assumed to be 0.06% of the whole length. If the assembly is made of mild steel, at room temperature this amount of deformation is still within the elastic range. Consequently, the columns *BB* may be safely expanded to this extent by any mechanical means, for example by lifting jacks; they will recover their initial length after removing the jacks. If the repair welding is being made while the columns *BB* are under constraint, then *after complete cooling of the weld* the removal of the jacks will cause the same contraction in all three columns, and no residual stress will be left in the assembly, other than that which may exist at and near the weld.

Thermal Control.—The same purpose can be achieved by *preheating* the columns *BB* to some 220°F., Fig. 4, at which temperature the expansion will be equal to 0.06%. The cooling of the *columns BB must not take place* before the weld is completely cooled; otherwise, some residual stress will develop. For it is seen from Fig. 4 that above room temperature, say at 180°F., there still remains a great deal of shrinkage to take place in cooling to room temperature, and consequently high residual stress may occur. There is no reason why this stress should disappear if all three columns are cooled *simultaneously* down to room temperature.

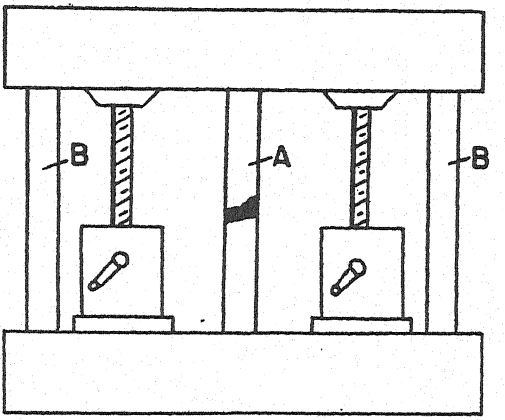


Fig. 8—Semi-Rigid Frame, Illustrating the Mechanical Control of Residual Stresses by Deformation of Structure Before Welding

Consideration of Fig. 4 suggests that no shrinkage and no residual stress will develop at any intermediate temperature thereafter, if the three columns are simultaneously cooled from the temperature marked by letter *L* at which temperature the shrinkage is exactly zero. Owing to the fact that the metal adjacent to a weld reaches all possible temperatures between the melting point and the surrounding plate temperature, it will not be possible to find a temperature corresponding to the letter *L*, Fig. 4, at which the shrinkage will be exactly zero, except possibly for parts which reach a very high temperature. In welding, this temperature will be generally found above some 1200°F. so that this treatment will become equivalent to a stress-relieving heat treatment.

Relief of Residual Stress

The aim of this treatment is to remove the already existing residual stress and not to prevent its occurrence. This is achieved by forcing upon the object a plastic deformation in such a way that its effect will be opposite to that of the shrinkage.

Stress Relief Heat Treatment.—This is the most common and reliable method of stress relieving. It has been noted in Fig. 4 that above some 400°F. the maximum elastic strain which a mild steel 1020 is capable of

withstanding in direct tension is smaller than it is at room temperature. Consequently, any residual elastic strain which is in excess of this maximum will be ironed out by plastic flow as soon as the reheating temperature exceeds 400°F., provided the state of the residual stress is similar to that of direct tension. Time of soaking is an important factor, since at high temperature metals may creep even under continuously decreasing load, but as a rule the higher the temperature, the greater will be the relief of stress. The detailed method of treatment is described in Chapter 32B.

Quite generally and regardless of the state of stress, welded mild steel soaked for a sufficient length of time at 1200°F. will be found almost free of residual stress, when properly cooled down to room temperature.

It must be remembered that before reaching room temperature there will still be a wide range of temperature at which the thermal expansion will considerably exceed the maximum elastic strain (see Fig. 4) and it has been shown previously that under these circumstances any marked difference in temperature is likely to set up a new residual stress.

In view of this, articles of widely variable thickness should benefit from an especially low rate of cooling; in some cases as much as 48 hr. may be necessary for completion of cooling. Of course, articles of uniform wall thickness, for example, pressure vessels, may be brought down more quickly with doors of the chamber open, and they may even be withdrawn from the chamber before the completion of cooling. But as a safe rule, no member may be withdrawn before a temperature is reached at which the thermal expansion has become entirely elastic. This would be at, roughly, 340°F., point K in Fig. 4, for mild steel. Particularly complicated structures, brittle and hardenable steels must be brought down to much lower temperatures (in extreme cases to as low as 200°F.) before opening the furnace, to preclude any possible thermal stress.

Overstressing.—It has been shown previously that residual stresses in weldments are the result of interaction between parts which have suffered a permanent set and parts which have not.

In the particular case of welding the permanent set is a shrinkage. However, similar interaction would occur if the permanent set would be an expansion, but the sign of the residual stresses would be reversed. Thus, superimposing a permanent elongation upon the shrinkage would result in a relief of the residual stresses set up by welding. This is the aim of overstressing.

Consider, for example, the assembly in Fig. 6 and assume again that bar A and columns B have equal cross-sections. With reference to the previous example, the bar A experienced a permanent plastic set of -0.09% and a residual tension of $+18{,}000$ psi. At the same time the columns B were subject to a residual compression of -9000 psi. If the assembly is now loaded in uniform tension up to, say, 10,000 psi., then the total stress set up in the bar will be 28,000 psi. and only 1000 psi. in the columns. Additional increase of the external load up to 20,000 psi will bring the bar well above the yield point, which is about 34,000 psi. for steel 1020, and if not restricted the bar would experience a definite permanent elongation. Because of the restraint upon the bar by the columns, only a small elongation will result, and additional residual stresses will be set up in the assembly

of opposite sign to those originally present. Thus, the original amount of residual stress will be reduced.

Whatever is the amount of the elongation, it must be such as to bring the stress in the bar down to the elastic limit under the combined effect of external load and residual strain; otherwise additional flow will start. Thus, the stress in the bar will be reduced by 38,000 − 34,000 = 4000 psi., and the residual stress left after the external load is removed will be 18,000 − 4000 = 14,000 psi. No further decrease of residual stress will now occur unless the external load is brought above 20,000 psi., so that the stress in the bar could again exceed the elastic limit. Gradual increase in load will cause gradual relief of residual stress in both bar and columns. Complete relief under *uniform* external tension will take place when stresses become equal in bar and columns. But to make the relief possible, the stress in the bar must be kept at the elastic limit. Thus, complete relief of residual stress under uniform tension is possible only when the elastic limit is exceeded everywhere. Conditions may, of course, be different if the external load is not a uniform tension. In particular cases the peak of the residual stress may be decreased substantially before the over-all elastic limit is reached. It is, however, doubtful whether complete relief can be achieved in this way, especially in view of the possibility of setting up new residual stresses due to a non-homogeneous loading.

Shrinkage

The factors responsible for shrinkage distortion are basically the same as the factors favoring residual stress which have been considered previously. But there is no simple relation between shrinkage distortion and residual stress. By shrinkage distortion is meant the over-all change in shape and dimension caused by welding. In special cases this change may be insignificant, yet residual stress may be high, if, for example, the parts to be welded are firmly held everywhere during welding. Conversely, great apparent distortion may be connected with only small residual stress, if welding is made on highly preheated parts, which are easily deformed.

The extent and amount of shrinkage distortion are widely dependent on the orientation and geometry of welds.

As a rule shrinkage will be smaller in the *direction* of weld than *transverse* to the weld, because in the longitudinal direction differently heated zones will be more in conflict than in the transverse direction. However, high transverse rigidity may easily upset this rule. In neither case will the shrinkage become very important. For example, the over-all shrinkage is reported to be: (1) 0.1% in arc-welded plate girders; (2) 0.05% in arc-welded lattice trusses; (3) 0.03 to 0.04% in welded ships, in length. This is no longer true when the welded structure undergoes *buckling* or angular *distortion.*

Angular distortion is a result of an unsymmetrical shrinkage. It may become important if the structure offers little rigidity in the direction in which the angular distortion is going to take place. This is particularly true if the shrinkage is not uniform across the *thickness.* Consider, for example, in Fig. 9, a butt-welded joint made in several beads. After the

first bead has been laid and cooled down to room temperature, the joint will no longer be able to shrink freely in the transverse direction. Thus, the shrinkage of the second layer will be impeded by the resistance of the first layer, and since these two actions are not in line, angular distortion will result. Angular distortion will increase gradually as welding proceeds, provided the subsequent beads are deposited in the same way as the second one. Likewise, a bead deposited on the upper face of a plate will tend to make the plate curl and buckle in the longitudinal direction, Fig. 10.

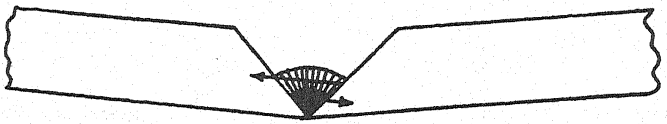


Fig. 9—Sketch Illustrating the Tendency of Multiple-Pass Fusion Welds to Produce Distortion

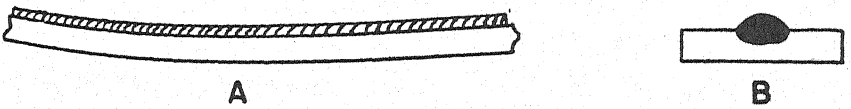


Fig. 10—Sketch Illustrating the Effect of Longitudinal Weld Shrinkage in Producing Distortion

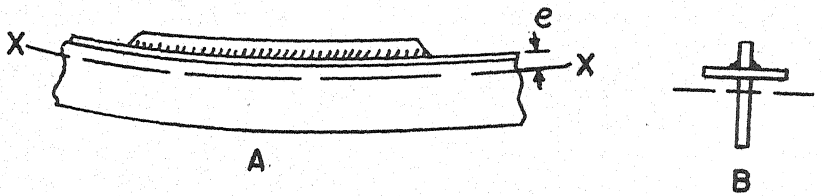


Fig. 11—Sketch Illustrating the Effect of Eccentrically Placed Welds in Producing Distortion

Unsymmetrical shrinkage with respect to the *width* may also cause angular distortion. So, for example, marked curvature may occur in composite beams having continuous fillet welds located eccentrically with respect to the gravity axis, x–x, Fig. 11.

Finally, unsymmetrical shrinkage in continuous welding *along* the seam is revealed by gradual closing of the space between two butted plates.

Control and Removal of Shrinkage

Proper design and proper welding technique are highly effective in controlling most of the angular distortion caused by welding. Spacing and angular *allowance deductions*, whenever possible, are convenient means to overcome this trouble in small structures. For medium structures *tack*

welding and jigs may prove more suitable provided they are strong enough to prevent any angular distortion. Finally, proper welding *technique* and *sequence* may be the only possibility in very large structures.

The correct design of a welded structure plays an important role in avoiding much of the trouble caused by distortion. By correct design is meant the planning of the *location* of welds in such a way that partial angular distortions caused by individual welds will cancel each other. The same result may be achieved by a proper *sequence* of welding.

There are no standard rules which can be recommended for this purpose, as the amount and extent of distortion cannot be computed from the factors available at present.

The two following recommendations may serve as a general guide:

1. Symmetrical arrangement of welds and symmetrical sequence of welding with respect to the axis of the welded member.
2. Location of welds at parts whose shrinkage is less liable to cause general distortion; as a rule at parts easy to straighten.

The second recommendation provides also a convenient means to eliminate any distortion which may occur in spite of the precautions taken before welding.

Removal of Shrinkage Distortion

The means by which distortion, mainly angular distortion, can be eliminated after welding are basically the same as those intended for stress relieving. For in both cases the cause is the same, namely, the tendency for the parts reaching the higher temperatures to upset plastically. The effectiveness of the different treatments reviewed previously, such as heat treatment, overstressing and peening, is difficult to estimate since nothing quantitative is known of the plastic behavior of metals under the conditions considered. Most of the expedients adopted in the industry are based on experience.

HEAT FLOW PROBLEMS

Fourier's Problem of the Quasi-Stationary State of Heat Flow During Welding. Use of Isotherms

Particular Features of Heat Flow in Welding

Compared to other problems of heat flow in bodies, the problem of heat distribution during fusion welding (and oxygen cutting as well) exhibits two particular features: first, the *heat source* (arc in electric welding, torch in gas welding) instead of being stationary moves on the surface of the piece to be welded with a speed which is usually constant; second, if welding is performed over a sufficient length, a state called *quasi-stationary* is soon created in the welded article.

To define this state let us assume an observer to be stationed at the source of heat during welding. Then, if the quasi-stationary state is

reached in the piece, the observer will notice no change in the temperature distribution around the heat source. To look at it in another way, let the temperature distribution around the heat source be represented by a hill, the isotherms being the contour lines of the hill (lines in Fig. 12); then, in a quasi-stationary state of heat transfer the hill will move as a rigid body on the surface of the plate without undergoing any modification either in size or shape.

As a consequence the traces left on the surface by different isotherms will become straight lines parallel to the direction of welding.

The establishment of the quasi-stationary state can easily be demon-

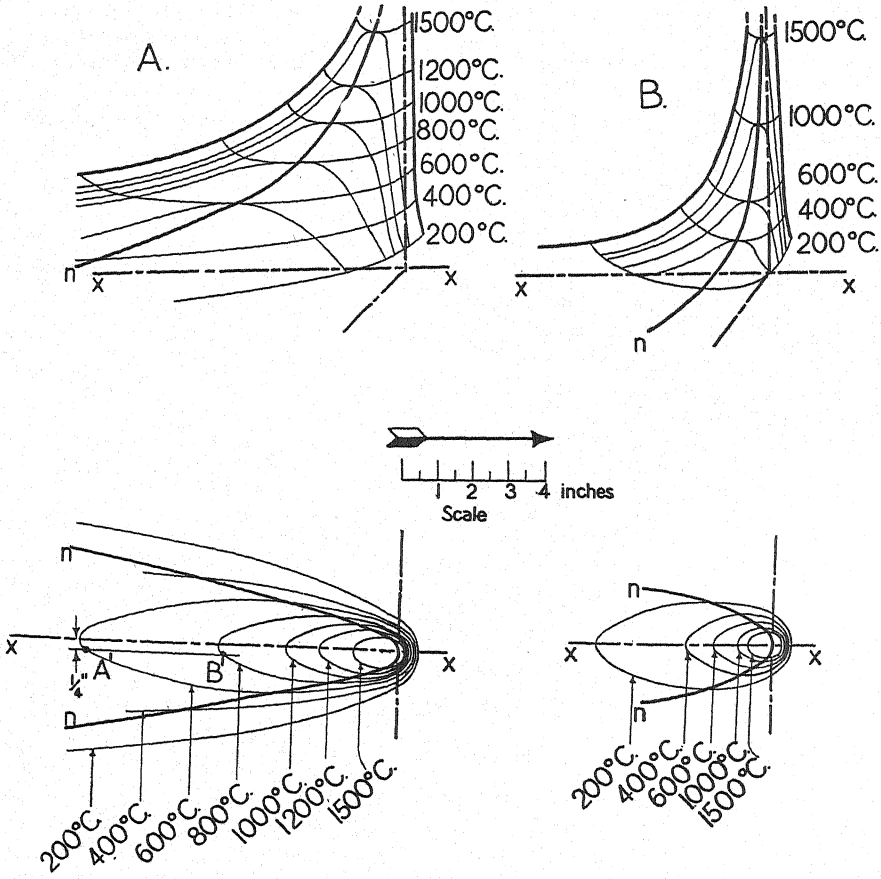


Fig. 12—Temperature Distribution Around the Heat Source

(Left) Thin plate (0.2 in. thick). (Right) Very thick plate (more than 4 in. thick). (Top) Representation in form of a hill. (Bottom) Representation in topographic projection.

n-n—Locus of maximum temperature.

Plate—low carbon steel, current intensity, 200 amp., welding speed, 8.0 in./min.

strated by means of the zones of different color, which form on the polished surface of a steel plate during welding. As is well known, these colors are formed at definite temperatures so that the maximum temperature reached by different parts of a p'ate can be determined. When the thermal state is quasi-stationary, these zones become parallel to the direction of welding.

Theoretical Approach

The establishment of a quasi-stationary state can be accounted for by the general equations of heat flow. A solution is then obtained with the desired degree of precision for most practical cases. However, the usual assumption is involved in such a solution, namely, that the physical characteristics of the material such as specific heat, density and heat conductivity are independent of the temperature. As previously seen, this assumption is by no means true, and a correcting factor will be generally needed to adjust the formula to experimental results.

To simplify the calculations two additional assumptions are made:

1. The heat source is a point. This assumption is satisfactory for electric welding with small electrodes, but is only a rough approximation for gas welding and cutting.

2. From large welded pieces there are no heat losses to the surrounding atmosphere. In general this assumption is supported by experiment, and is explained by the fact that the heat conductivity of metals is usually much greater than their heat transmission through the surfaces. This may not be true for certain special steels with low conductivity, but, even for these, the assumption is advantageous because it enables an investigator to account separately for the influence of each factor, which is sometimes difficult in an experimental study.

Practical Results

The heat distribution of the quasi-stationary state during welding is best understood when examining families of isotherms drawn around the heat source, Fig. 12. The general features of heat flow involved in welding are at once apparent from these isotherms, namely:

1. The rise of temperature, in front of the heat source, is steeper than the fall of temperature behind the source.

2. The points on the plate passing through the maximum temperature at the same instant are located on a line, *n*, which is curved backward. This is due to the finite speed of heat flow in metals, which delays the occurrence of the maximum temperature in parts of the plate more distant from the weld seam. The curve *n* separates the part of the plate (in front of it) with temperature rising, from the part (behind it) with temperature falling at the same instant.

3. As a consequence of a much steeper temperature gradient ahead of the electrode during welding, brought about by the movement of the heat source relative to the direction of heat flow, the metal is more quickly heated to, than cooled from, a given temperature. The difference is particularly pronounced at the line of welding and it decreases gradually for the more distant portions of the plate.

The influence of each factor is also explained more readily by comparison of the corresponding isotherms:

1. *Thickness.*—As shown in Fig. 12 for welding conditions in which there is the same rate of heating, a wider heat-affected zone is created in the thinner plate (thickness—0.5 cm. = 0.2 in.) than in the thicker one (of almost infinite

thickness). As a result the temperature fall (gradient) is less pronounced in the former one. At the same time the lag of the curve *n* is greater, this owing to the smaller cross-section and consequently greater resistance offered to heat flow. (The electrical analogy is obvious).

2. *Nature of Material.*—The two lower diagrams, Fig. 13, indicate that greater heat diffusion in aluminum (*D*) results in a more circular shape of isotherms than in iron (*C*). The same applies to the curve *n*, which, as ought to be expected, is also nearly straight.

3. *Current Intensity.*—From the two left-side diagrams, *A* and *C* of Fig. 13, it is apparent that increasing current intensity widens the heat-affected zone without much changing the shape of isotherms. On the contrary:

4. *The speed of welding* affects mostly the shape of isotherms. The higher the speed, the more elongated are the isotherms and the more pronounced the lag of the curve *n* (compare the two diagrams, *A* and *B*, on the top of Fig. 13).

5. *Preheating* decreases only the range between the considered temperature and the initial temperature. Neither the shape nor the size of the isotherm is

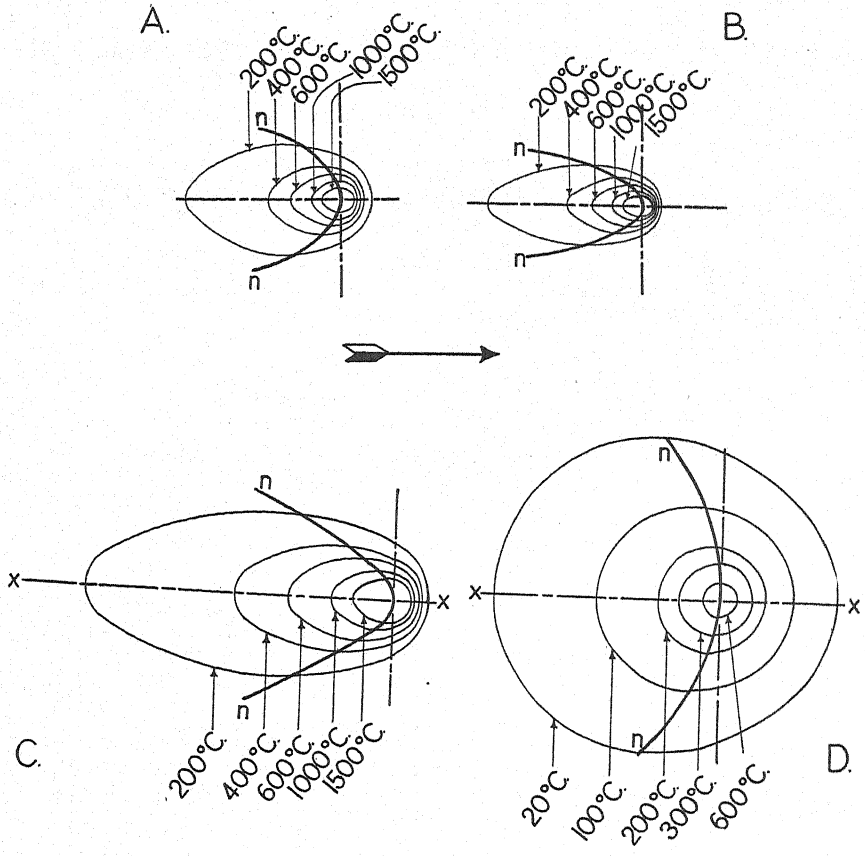


Fig. 13—Temperature Distribution as a Function of Current Intensity, Welding Speed and Nature of the Base Metal. Very Thick Plate

A—Low carbon steel, 200 amp., welding speed, 4 in./min.
B—Low carbon steel, 200 amp., welding speed, 8 in./min
C—Low carbon steel, 400 amp., welding speed, 4 in./min.
D—Aluminum, same heat input and same welding speed as for *C*.

changed, but the same isotherm belongs now to a higher temperature. As a result the fusion zone, i.e., the zone comprised within the isotherm of the melting point, is widened.

Application to Welding Practice

One of the most useful applications of diagrams like that drawn in Fig. 13 consists in evaluating the time needed for a given point of the welded piece to cool down from a higher to a lower temperature. As will be seen later, this is particularly important when dealing with the problem of weldability of high carbon or low alloy steels.

For the present application it will be recalled that in the quasi-stationary state the families of isotherms move in the direction of welding with the same speed as the electrode itself. Therefore, the time interval in which a given point of the piece is passed by two given isotherms is equal to the distance between the isotherms divided by the speed of welding.

For example, in the case of the left-hand diagram, Fig. 12, the distance between two isotherms marked 800° and 600°C. (1479° and 1110°F.) $^1/_4$ in. away from the line of welding, X–X, is $A'B' = 4$ in.

Since the speed of welding, v_0 is 8.0 in. per minute, the distance $A'B'$ will be covered in $A'B'/v = 4/8.0 = 0.50$ min. In other words, it would take 0.50 min. to cool any point located $^1/_4$ in. away from the line of welding from 1470–1110°F. More generally, if the distance between the isotherms of Fig. 12 is read on a scale v_0 times greater in the direction of welding, the diagram, instead of marking the location of temperatures on the surface of the plate *at a given moment*, will indicate the intervals from one temperature to another for each point *of a given cross-section*.

The average cooling speed between two successive temperatures is also easily computed by means of these diagrams. Thus, in the case of Fig. 12 the average cooling speed between 1470° and 1110°F., $^1/_4$ in. away from the line of welding, is $(1470 - 1110)/0.50 = 720$°F./min.

It is found that the cooling speed decreases as: (1) the heat input per linear inch of welding increases, and (2) the preheating temperature increases.

The numerical relation between these values depends upon the nature and size of specimens to be welded and also upon the welding process involved. All these influences, however, are reflected in the general aspect of the isothermal diagrams, the knowledge of which appears therefore to be of outstanding importance to the welding practice.

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CHAPTER 2

FUNDAMENTALS OF WELDING METALLURGY*

The Metallurgy of Ferrous Welds, Solid Constitutional Relationships in Plain Carbon Steel, Austenite Transformation in Plain Carbon Steel, Constitutional Relationships and the Austenitic Transformation in Alloy Steel, Metallurgy of Welds in Nickel and High-Nickel Alloys, Copper and Copper Alloys.

THE METALLURGY OF FERROUS WELDS†

WELDING processes for ferrous materials may be divided primarily into methods which require heat or which require the application of heat and mechanical pressure. To assure a permanent and homogeneous weld junction, it is necessary to bring the parts to be united into such close contact that adjoining surfaces are held within a mutual atomic force field of attraction. Heat and pressure or heat of fusion to form a contiguous pool between parts are always employed in operative processes for this purpose. The metallurgy of welding is, consequently, concerned with the properties of the metallic materials which are involved and the mechanical and thermal effects established during the welding operation.

Materials Employed in Welding

The study of the weld metallurgy embraces three or less different masses of metals, which may include the two base metals consolidated and added metal to constitute part of the weld. A fourth metal may be concerned if a backing strip or ring is employed. Consideration of the weld metal involves reactions in its liquid state, the mechanics of solidification and its thermal history in the solid state, both as established by the welding process and the auxiliary heat-treating procedures. The base metals may contribute dilution or alloying effects, but aside from such diffusion processes they are to be considered mainly only from the viewpoint of the thermal effects imposed upon their solid states. In the following discussion

* Prepared by a committee consisting of E. F. Wilson, Babcock & Wilcox Co., *Chairman*; O. B. J. Fraser, International Nickel Co.; O. H. Henry, Polytechnic Institute of Brooklyn; G. O. Hoglund, Aluminum Company of America; I. T. Hook, American Brass Co.; A. B. Kinzel, Union Carbide & Carbon Res. Labs.

† The metallurgy of ferrous welds is a specialized branch of the general metallurgy of steels. Only a brief survey of the fundamentals can be presented in this chapter. An excellent approach to this subject is available in *Welding Metallurgy* by Henry and Claussen published by the AMERICAN WELDING SOCIETY.

we shall concern ourselves with the principles of fusion welding and particularly with the metallic arc method as illustrative of others which are basically similar. Other fusion welding processes include the oxyacetylene, atomic-hydrogen and carbon arc.

Base Metal to Be Welded

Base metals to be welded are limited for practical reasons to the compositions and forms which are amenable to commercial fabrication without appreciable defects. Their weldments should also possess mechanical properties permitting an acceptable construction according to engineering standards. Restrictions in base metals are established to avoid defects in the fusion process or weld embrittlement during cooling from the welding heat. Codes and specifications have been established which restrict the carbon and other hardening elements to insure weldability. This does not infer the inapplicability of steels outside the codes, but their limitation to certain purposes and the necessity of special precautions during the welding.

Usually plain carbon steels utilized in conventional applications are limited to under 0.35% carbon when they are to be welded with ordinary practices. Manganese and silicon contents should be within such limits as to assure a satisfactory practice of steel manufacture, particularly in respect to deoxidation. A limitation of these elements may be necessary to reduce contribution to any embrittlement in conjunction with other elements. Phosphorus and sulphur are held to the accepted maxima established for the method of steel manufacture which is employed. Other elements are restricted to insure a similarity of product and avoidance of unforeseen difficulties in fabrication.

The composition of alloy steels is also carefully specified in view of their more difficult welding characteristics and resulting mechanical properties. For example, elsewhere in this chapter will be found a description of some "low alloy steels" in which the weld hardening is limited by balancing the effect of special elements and reduction in the carbon content. Other alloy steels may require special welding practice for their best utilization, and the AMERICAN WELDING SOCIETY has attempted to classify these according to similarity in order of weldability in the "Standard Qualification Procedure." Consideration has also been given as to whether these materials are to be welded in the as-wrought, cast or forged forms and in accordance with the service conditions which are to be met.

Added Weld Metal

Filler metal to be added in molten form to insure a complete weld junction is utilizable in wire or rod shapes and is designated as electrodes in the electric-arc process or weld rods for gas welding. The chemical composition of the weld rods and electrodes is usually not specified, except for general type, since nominal analyses alone do not indicate their welding properties. The only real criteria of their satisfactory performance are the results of the actual welding operation and the mechanical properties of the deposited weld metal individually and as a part of the base materials.

The composition of the solidified added weld metal should approach that of the base materials where it is desired to avoid any great discontinuity in physical or chemical characteristics. The composition of the rods is based on expected losses of elements and on good welding characteristics. The high temperatures encountered in fusion, especially in the electric arc, have a great influence upon the welding characteristics of the rod if there is any appreciable deviation from the optimum compositions established by experience. Electrodes may comprise bare or coated rods. The latter consist of a metal core surrounded by a sheath of carefully selected components which fuse to a protective slag during welding. The coating also contributes to reliable operation of the arc.

Carbon Content of Electrodes

Carbon contents of electrodes are based on the expectation that some part will be lost by oxidation during fusion in the arc. This loss will vary from 0 to 20% and above, depending on coating composition. In bare wire electrodes, which are not utilized except for work of lower requirements, the carbon loss may be as much as 25 to 75%. Oxidation of carbon in coated electrodes can be limited by adding carbon compounds or other reducing elements in the coating material. Increasing these additions in the coating can accomplish carburization. This carburization may be desired for wear resistance or other reasons.

The carbon content of plain carbon steel electrodes is ordinarily regulated with other elements according to the final mechanical properties desired. The A.S.T.M. Specification A233–42T classifies arc-welding electrodes in part on their ability to meet, respectively, 45,000, 60,000 and 70,000 psi. tensile strength requirements in the stress-relieved condition. A similar gradation for oxyacetylene gas-welding rods is involved in the revised specifications, see chapter 27B.

In oxyacetylene welding the losses of carbon and other oxidizable elements can be adjusted by the flame regulation.

In alloy steels the carbon content is frequently limited and its strength-contributing effect replaced by the addition of other elements. In corrosion or heat-resisting alloys the carbon content may be determined on the basis of its chemical response in service. In alloyed wear-resisting steels carbon plays an important part because of the hardness of the complex carbide. The carbon content of cast-iron rods is regulated in conjunction with the silicon content to control its melting temperature and graphitizing tendency.

Silicon Content of Electrodes

The silicon of the plain carbon steel electrode is determined to a large extent by grade of metal used. This is commonly basic open-hearth rimming steel of low metalloid content. A low silicon is said to give better arc characteristics and is less apt to contribute to a viscous slag by the formation of silica of high melting temperatures. Silicon is oxidized early in the fusion of the steel rod and in preference to carbon. Since on oxidation of silicon, refractory silicates are formed which may be retained as inclusions, unless other fluxing oxides are present oxygen removal by con-

version to carbon monoxide which escapes in gaseous form from the molten metal is sometimes preferable. The final silicon in the solidified weld metal contributes a strengthening and hardening effect by solid solution in the ferrite.

In oxyacetylene welding, silicon is less critical because it is not necessarily subject to the same extent of oxidation. However, it is likewise objectionable, unless low manganese is present to prevent formation of refractory silicate slags and inclusions.

Other Elements in Electrodes

The manganese content for weld rods and electrodes should be sufficiently high to insure that the steel is properly made. It should not exceed the content above which it increases too measurably the hardening effect of the carbon.

Phosphorus and sulphur in weld rods are held to the lowest possible limits, both on account of their undesirable behavior during welding and adverse influence on the final mechanical properties of the weld metal. Oxygen contents are not often or easily determined in routine analysis, but are presumed to be indicated by welding performance tests.

Coatings and Fluxes

Weld rods, unless provided with a protective atmosphere to prevent oxidation, should be coated with slag-forming materials. These prevent losses by atmospheric oxidation or pickup of oxygen and nitrogen and assure consistent and acceptable weld metal properties. Electrode coatings are also desirable to obtain good arc characteristics during the welding operation. Rods for oxyacetylene welding are usually uncoated, but are protected by the welding atmosphere.

Bare rods have been almost entirely displaced by the coated forms in metallic arc welding, except for work of the least critical nature. However, even the so-called bare rods may have a thin formation of chemically applied oxides which favorably affect their electrical behavior in the arc but do not provide appreciable protection against oxidation of elements in the rod. Light coatings of this nature have been generally replaced by thicker and mechanically applied coatings consisting of oxidic components. These can be compounded so that they are reactive with a corrective or protective tendency, or else moderately inert in respect to the weld metal.

Reaction Between Weld Metal and Coatings

The behavior of electrode coatings can be classified according to their metallurgical (pyrochemical), physical and electrical properties. In their metallurgical reactivity an important characteristic would be the ability of the fused coating or slag to assimilate metallic oxides, such as FeO, MnO, etc., from the liquid metal, by solvation in the slag and reaction to form stable compound oxides. Ferrous and manganous silicates are typical examples of this combination.

At any temperature there is a definite distribution ratio between the respective concentrations of oxides dissolved in associated slag and metal.

This ratio can be modified by increasing the solubility in the slag and so removing dissolvable oxides from the metal. It applies only, however, to the active solute, i.e., that not combined as compounds of oxides. Hence, the presence of reactive oxides, such as silica, has a deoxidizing effect upon the metal by combination with FeO or MnO, which are otherwise free soluble oxides. These silicate compounds are then "unavailable" for solution in the molten metal and exist as slag. Elevated temperatures tend to dissociate these compounds and their stability varies with the proportions of the simpler oxides involved.

Alloying additions may be introduced into the weld metal from ferro-alloys present in the coating. This permits several weld metal compositions with the same core metal by adjusting the coating composition as required. Sometimes the additions are just sufficient to compensate for oxidation losses in the metal during fusion and have no alloying contribution.

Carbon and its compounds are frequently added to form protective atmospheres. These prevent atmospheric oxidation by reacting preferentially with coating oxides to protect the metalloids in the core metal from loss. The formation of a neutral or reducing atmosphere of carbon monoxide or hydrocarbons supplants that of the air in the arc zone. Moisture formed or released from carbohydrates and hydrous compounds in the core is usually held undesirable, but frequently this is chemically released during decomposition and evaporated by the welding heat before it can be introduced into the arc region.

Physical Properties of Fused Coatings

The desired physical properties of the coating should include a temperature of fusion somewhat above that of the core metal. This insures a protective, solid sheath extending slightly beyond the metal core at the arc tip with a protective effect. Furthermore, the higher fusion temperature, by preventing the premature running off of the slag, maintains a protective slag layer on the surface of the molten metal. Other desirable qualities of the fused coating or slag would be a low density and low viscosity to aid its flotation from the mixed slag and molten metal. A rapid coalescing rate of the slag also helps to prevent entrapment of the slag in the solidifying metal.

Related to its miscibility, the slag should have some wetting action on the molten metal in order to spread and cover it completely. The adherence of the slag to the molten drop during the transfer from the end of the electrode to the molten pool is also governed by the wetting tendency. Size of the individual droplets and their transfer mechanics are also believed to be influenced by these slag characteristics.

The interfacial reactions or wetting qualities of the slag with the molten metal are also revealed in the regularity and smoothness of the solid surface of metal deposit after the final slag removal. Removal of the solidified slag should be accomplished easily without adherence of particles to be entrapped by a succeeding layer of weld metal. A glass-like type of slag with a thermal contraction coefficient quite different from that of steel aids in this removal, since it is friable and breaks upon cooling.

Important characteristics of the slag are reflected in its thermionic

behavior in the electric arc. Some oxides of iron and titanium and some calcium compounds are said to be stabilizers, since they lower the required voltage for a sustained arc or increase the distance from electrode to work which will maintain a continuous arc. They are also believed to aid the pinch effect or contraction and propulsion of the molten globule from the end of the rod and thus permit position welding, i.e., in vertical and overhead positions, by offsetting gravitation effects. Other compounds, such as alumina, are reported to raise the operative voltage and are classed as non-stabilizers.

Pyro-metallurgical effects of the coating are manifest in the absorption of heat during fusion and dissociation of compounds. This varies with the coating thickness. Somewhat higher arc amperages are permissible as the heat absorption increases. Heat is also conveyed from the arc and the molten metal by convection on liberation of gases from components in the coating. The insulating effects of the slag blanket to lower the cooling rate of the weld deposit are primarily concerned with the amount and density of the coating.

Fluxes may be added directly to the weld groove instead of being introduced as coatings. The submerged melt welding method employs such additions. Electrical properties other than thermionic are important in fluxes which are so utilized.

Coated rods are not usually employed in oxyacetylene welding. A certain amount of metal oxidation may occur despite the employment of a neutral gas flame. For this reason the weld rods invariably contain silicon and manganese to care for this oxidation and in such proportions that the oxide products form a slag of suitable viscosity. Alloy steels of high chromium content usually require added fluxes which dissolve or float the refractory chromic oxide formed.

Reactions in the Molten State

When the weld metal is fused by the metallic-arc process it is subject to a heterogeneous system of successive and somewhat concurrent reactions. It is reactive with the slag formed from the rod coating, the atmosphere in the arc region and the base material to be welded. The corresponding periods in the process are those of rod fusion, transfer of the metal droplets through the arc gap, incorporation into the liquid pool of weld metal and admixture with the base metal. Controlling these operations are the properties of the reactants and electrical behavior of the arc. The latter may be reflected in part by the size of the metal droplets, their detachment and transfer characteristics, mechanical agitation, heat input and metal temperature, which is principally governed by the welding current. Modifying the results of heat input are cooling effects such as heat absorption by fusion or reaction, thermal convection by the liberated gases and the thermal conduction of the base metal. This last can be adjusted somewhat by preheating of the base material.

Temperatures of the metallic arc are reported to attain about 6000°C. Under these conditions, chemical equilibrium has been found to be reached very quickly, but direct observations are precluded by the rapidity and intensity of the reactions. However, end reactions can be examined and

related to tendencies recognized as the probable results of the simpler reactions in the kinetic chain.

In the composition of steel electrodes the commonly considered elements are manganese, silicon, carbon, phosphorus and sulphur, plus the specially added alloy elements and small amounts of incidental oxygen, nitrogen and hydrogen. The first three elements are quite readily oxidized, either by the oxygen of the atmosphere or free oxides from the coating. Since the elements other than the first three are restricted to low contents in plain carbon steel, their oxidation is proportionally negligible.

Proprietary preferences govern the composition of electrode coatings and the slag that results on fusion. Without consideration of their more complex association as silicates or other compounds, the oxides of primary valencies are classified in Table 1.

Table 1—Oxides of Primary Valencies

Alkaline oxides—	K_2O, Na_2O, etc.
Basic oxides, Group II —	CaO, MgO, FeO, MnO, etc.
Group III—	NiO
Slightly acid oxides—	Fe_2O_3, Al_2O_3
Acid oxides, Group I—	SO_2, CO_2
Group II—	P_2O_5, SiO_2
Group III—	Cr_2O_3, V_2O_5, TiO_2, MoO_3

Group I is gaseous, while Groups II and III are in the solid state at room temperatures. Group II constitutes oxides of specifically added alloy elements.

The stable compounds formed by interaction of single oxides in fused coating slags are frequently basic or alkaline silicates or compounds of titanium oxide. Contents in excess of these combining proportions are described as free oxides and may be available to react with or dissolve in liquid weld metal. Others may only act as a body to the slag to dissolve other oxides which they may share with the weld metal.

Oxides Soluble in Liquid Steel

The uncombined or free oxides of FeO and MnO are soluble in liquid weld metal in some proportion to their content in the molten slag of the electrode coating. These solubilities are increased by higher temperatures of superheat which also effect some dissociation of compound oxides and so raise the free concentrations capable of dissolving in the weld metal. In the case of ferrous oxide the maximum oxygen solubility which can dissolve in iron or very low carbon steel, according to Chipman, is:

$$\log \%\ \text{oxygen} = 4860/T + 1.935$$

where T is the absolute temperature°C.

The amount of free FeO or MnO imparted from the coating slag determines the respective losses of the metalloids manganese, silicon and carbon from the original core metal of the electrode. Using the convention of brackets to represent components dissolved in weld metal and parentheses for those in the slag, the oxidation of these elements in the metallic pool is in accordance with the reactions:

$$[FeO] + [Mn] \longleftrightarrow [MnO] + [Fe]$$

$$[2MnO] + (SiO_2) \longleftrightarrow (2MnO{\cdot}SiO_2)$$

$$[2FeO] + (SiO_2) \longleftrightarrow (2FeO \cdot SiO_2)$$

$$[FeO] + [C] \longleftrightarrow [Fe] + CO$$

$$[MnO] + [C] \longleftrightarrow [Mn] + CO$$

The diffusion of soluble, free oxides from slag to weld metal up to the limit of their saturation can be indicated by the expressions:

$$(FeO) \longleftrightarrow [FeO]$$

$$(MnO) \longleftrightarrow [MnO]$$

In order to protect the weld metal from serious loss in the oxidizable elements, ferromanganese and ferrosilicon may be added as coating ingredients to oxidize in preference to them. Carbon compounds are added for a similar purpose. Other oxides soluble in liquid steel, such as NiO or Cr_2O_3, may be involved in alloy steel electrodes and weld rods. Usually their formation is limited by protective slags or surrounding atmospheres of a reducing nature.

Ferrous and manganous oxides usually contribute to improved slag fluidity and easier flotation by the weld metal pool. Silica and chromium oxide are usually more refractory and tend to a viscous slag.

Oxides Insoluble in Liquid Steel

A great many of the coating oxides are insoluble in molten weld metal and have little direct effect on slag-metal reactions. They may have, however, important functions of a physical or thermionic nature in the welding arc performance.

Silica, and correspondingly silicon present or introduced into the weld metal, is important as an oxygen remover, since it can eliminate soluble FeO or MnO as insoluble silicates. This deoxidizing effect is useful in preventing excessive reaction of these oxides with carbon, and porosity where the gaseous carbon monoxide is entrapped during freezing. It also influences the extent to which FeO and MnO may contribute to the physical properties of the solid weld metal as minute and dispersed inclusions.

Silica and silicates are essentially insoluble in liquid iron and steel. If entrained mechanically they may be slow to rise into the superimposed slag layer and may be retained as refractory inclusions in the solid metal. Highly siliceous slags are apt to be viscous.

Carbon is effective in removing soluble oxides from liquid metal as gaseous carbon monoxide of low solubility. This reaction does not always proceed to completion, however, and usually requires nucleation. Retarded gas evolution frequently becomes active during the solidification process and unless the gases can freely escape, entrapment with residual porosity may result. This tendency to porosity may be minimized by reducing the temperatures of superheat in the weld metal fusion by slowing down the rate of solidification to permit free gas evolution, by proper design of the weld groove so that the molten center of the weld metal will not bridge over by solidifying prematurely and, lastly, by eliminating soluble oxides which can react with carbon by conversion to their insoluble silicates or deoxidation to form silica.

Reactions with Phosphorus

Phosphorus under 0.040%, which is a usual maximum for ordinary grades of commercial steel, has no evident effect on welding in either weld rod or base metal. However, in the weld rod phosphorus contents of such an order that they aggravate the banding of ferrite and pearlite may cause foaming or increased spatter loss because of uneven fusion. Spotty segregation of phosphorus is also undesirable, since the low melting point of the ternary eutectic of iron, carbon and phosphorus may result in local softening or fusion. Little loss of this element is ordinarily observed in either bare or covered electrodes.

In fusion or in electric resistance butt and spot welding, moderate contents of phosphorus above normal, but insufficient to give brittleness in the product, have been reported to give good or improved weldability. This has been attributed to the lower heat input required for melting the steel. In forge welding the fluidity of the scale has been found to be increased by this element. However, in arc welding of thin gage material of higher phosphorus contents, a tendency to burn through has been observed. Where the phosphorus is sufficient to lower the melting point of the weld appreciably, less adaptability to overhead welding can be expected. The surface tension and adherence of the weld metal globules is lowered accordingly.

Reactions with Sulphur

Sulphur in the weld rod or base metal below some 0.05% and in the absence of any marked segregation has no noticeable effect on the welding operations. In a highly segregated condition or with larger concentrations, the weld rod shows uneven melting due to the low fusion point of the sulphide, together with spatter and foaming attending its oxidation and the formation of sulphur dioxide. For these reasons, free machining grades of steels are generally unsuited for welding applications.

High sulphur may also be indicative of improper melting practice in the manufacture of steel. Excessive oxides, often in the form of oxy-sulphides, may accompany insufficient desulphurization. Such inclusions have been observed to result in porosity in the weld metal or laminate ruptures at the weld junction when the oxides are spread out in the hot rolling operation. The low melting point of such oxy-sulphides aids in the spreading of these "laminations" in a continuous form.

Effect of Atmosphere on Molten State Reactions

During the welding process the molten metal may be reactive with oxygen, nitrogen or hydrogen or the gaseous compounds of these elements with carbon. In bare metal weld rods the reaction is direct, but in coated rods the slag is an intermediary during all or part of the molten state period.

Oxygen.—Oxygen is the most potent alloying element of this series and in the presence of molten iron tends to form the ferrous oxide FeO. Ferric oxides do not exist at elevated temperatures and in the presence of liquid iron. Sources of oxygen are the surrounding air, oxides from the

coating which are free to dissolve in molten steel, or dissociation of moisture present in the air or evolved from the coating ingredients. Bare rod electrodes may show somewhat over 0.2% oxygen in the final weld deposit, but of this amount probably less than 0.05% remains in solid solution in steel at room temperatures. Covered electrodes show much less pickup of oxygen, while in oxyacetylene welds the final content may be as low as 0.01%. At the melting point of iron covered with ferrous oxide, the maximum solubility is about 0.98%.

If oxygen-avid elements, such as titanium, aluminum or silicon, are introduced into the molten weld metal, then stable oxides are formed which are not easily reducible by carbon. The porosity formed upon solidification from carbon oxidation with the resulting liberation of carbon monoxide gas is consequently prevented. The melting temperatures and viscosities of these oxide products may restrict or regulate the use of such deoxidizers in welding operations. Relatively refractory oxides, such as alumina, for example, persist as uncoalesced and undesirable inclusions in the final weld metal.

Carbonaceous Gases.—The carbon monoxide and some hydrocarbon gases are carbonizing in respect to molten steel, while carbon dioxide and steam are oxidizing. These two opposite effects may practically neutralize each other at a balanced proportion for each temperature. Hydrocarbons and water may be derived from cellulose or other organic ingredients included in electrode coatings, while their oxidation supplies the carbon oxides CO and CO_2. In oxyacetylene welding the oxidizing and reducing gases in the flame may be controlled by proper proportioning.

Reducing or non-reactive gases lower the surface tension of liquid weld metal, presumptively by preventing the formation of thin but refractory oxide films. By their expansion and convection, liberated gases, particularly those of high thermal conductivity, convey heat away from the arc or welding heat source and prevent overheating of the liquid metal. This may help to eliminate porosity. Some heat can also be absorbed by the dissociation of polyatomic gases,but their recombination in cooler zones may nullify this effect. Rapid gas formation within the molten metal globule, which usually accompanies excessive oxidation, results in high spatter loss because of the violence of its liberation.

Hydrogen.—Hydrogen is soluble in molten iron up to some 0.005%. On solidification the solubility is greatly decreased, but may not be effective unless evolution can occur. The absorption of hydrogen occurs atomically. The atomic form may be derived from the dissociation of steam, hydrocarbons or molecular hydrogen by welding heat or in the electric arc. Carbon, manganese and silicon within the usual limits in steel have practically no effect on hydrogen solubility.

The absorption of hydrogen in liquid iron follows Sievert's law of variation with the square root of the gas pressure and is a function of the extent of thermal dissociation to the atomic condition. While hydrogen absorption is relatively small in percentage figures by weight, the volume capacity is more pertinent, especially in respect to porosity. This may be illustrated by the observation that a solidifying steel ingot may liberate some twelve times its volume of dissolved hydrogen. Part of this may appear as hydrocarbons formed by reaction with carbon in the steel.

The effectiveness of the atomic hydrogen arc process, particularly in welding alloy steels which form refractory and highly stable metallic oxides, is due to their reduction by hydrogen in the atomic condition. The heat of recombination of atomic hydrogen to the molecular form when released in close contact with the material to be welded is another important characteristic of this process.

Nitrogen.—Nitrogen absorption in molten metal can occur on contact with air, and it is one of the important functions of coating slags to prevent its assimilation. Protective gas atmospheres from the oxyacetylene process or from organic material in electrode coatings also contribute to this prevention. Weld grooves wide in proportion to rod size, frequently required because of heavy thickness of the base metal, may cause higher pickup of nitrogen, since the protection by a gaseous envelope is less easily maintained.

All industrial steels contain some nitrogen, and the residual amounts left in weld metal are these contents plus the changes that may have been accomplished during welding. In liquid iron or steel concentrations of nitrogen above some 0.04% may be present under equilibrium conditions. Metastably several times this figure may be absorbed and retained to room temperature. Quantities up to 0.2% have been observed when bare rod electrodes are employed. The final content is the higher the more rapid the cooling rate of the molten metal. Covered electrodes usually permit a nitrogen content in weld metal under 0.035%. This value has been empirically established as a permissible maximum for consistent metal properties.

Some evidence has been offered to the effect that nitrogen absorption is affected by the length of the arc gap or size of electrode used. It is apparent, however, that the rate of absorption depends on the dissociation of the molecular form to the atomic condition within the gap, and any circumstance that affects the arc operation is a controlling factor.

Aluminum, silicon and chromium are believed to aid the assimilation of nitrogen in steel. Manganese may increase the solubility, but in the concentrations characteristic of industrial steels no definite influence can be traced. The final content of nitrogen depends upon its introduction into the molten weld, since on cooling there is insufficient time for attainment of strict iron-nitrogen solubility equilibria. However, some removal may be accomplished by vigorous carbon monoxide liberation during the transfer from electrode to weld pool. The amount of nitrogen absorbed in the weld metal has been found to decrease with carbon, possibly through gaseous shielding or the sweeping-out action of the carbon monoxide evolution.

Inert Gases.—The influence of the gaseous atmosphere is felt in the electrical behavior of the welding arc. Doan has shown that in atmospheres of relatively inert gases, such as argon and helium, high voltages are necessary in order to sustain the arc; there is no pinch effect to aid the detachment of the molten globule from the end of the electrode, and no cratering occurs in the pool. The addition of a small amount of oxygen to the otherwise pure gases allows the formation of a crater, restores the pinch effect and consequently detaches the liquid metal in a succession of small droplets rather than in larger globules. Pure nitrogen, likewise, gives no cratering. Absorption of nitrogen in the weld metal has been found to increase on the addition of oxygen in a prevailing atmosphere of the former.

The exact cause of cratering is still undetermined, but is known to depend upon the presence of oxygen. The effects of the electronic bombardment in the arc stream and the differential of surface tension from center to sides, depending on the temperature gradient in the molten pool, have been considered as possible causes. Cratering is not dependent on fusion penetration, since this is increased by some diatomic gases, such as nitrogen, and by the employment of higher currents in the "inert" gases.

Cooling and disturbance of the arc gap by excessive gas liberation have been observed to give fluctuations in arc voltage. Arc wander is also evident if easily ionized oxides or stabilizers are absent. Spatter is evidently a matter of gas entrapment and its explosive expulsion. Some experiments with higher atmospheric pressures show that this pressure increase necessitates higher voltages to maintain the arc.

Solidification of Steel.—The physical properties of solid steel are influenced by the maximum temperature of superheat of its liquid phase and the rate and mechanism of its solidification. Characteristics inherited from these temperatures are only partly removed by extensive mechanical and thermal treatment of the solid metal. The differences between weld metal and forged and cast metals are in part attributable to the high heat of fusion in welding and the rapid solidification rate which succeeds it.

For purposes of description, the solidification of steel may be divided into the following processes, which are approximately consecutive; nucleation of atomic order, ordering of atoms into a crystallographic array, crystallization or granulation, segregation of elements between liquid and solid states, solidification shrinkage, gas liberation from the melt and diffusion of the segregated elements in the direction of homogenization. The time rate of freezing is the important controlling factor in each of these occurrences.

Atomic Ordering and Crystallization.—The solidification of steel is attended by a systematic arrangement of atoms from a disordered or random distribution in the liquid state into one of orderly spacing in their solid state. There is also an over-all condensation because of the closer packing of the atoms. A single system of orderly arrangement does not extend throughout the metal mass, but initiates from a number of sources called nuclei wherever a small aggregation of atoms can assemble into order and continue to grow. These nuclei develop to a crystal, which is an aggregation with the same anisotropic arrangement of atoms throughout and forming a coherent part of the whole. The significance of anisotropy is a difference of spacing in different cross-sections and along principal axes within the crystal. Consequently, crystals have unlike physical properties, depending on their orientation with respect to a fixed direction. The close packing and stable distribution of interatomic forces in a crystal make it an exceedingly hard and strong structure.

A perfectly formed crystal is bounded by a series of plane surfaces, characteristic of its chemical composition. This external appearance is indicative of the internal geometry of atomic lattices. Few industrial alloys, however, permit the formation of perfect crystals, since their growth is interrupted by adjacent crystals developing from near-by nuclei. The incomplete and necessarily irregular crystals are known as grains. They are strongly bonded together by the intergranular matter of randomly oriented atoms. The high strength of this intergranular material, together

with the differences in orientation among the constituent grains, results in a mass strength which appreciably exceeds that of a single crystal.

Dendritic Solidification.—Nucleation of molten steel does not usually initiate simultaneously throughout its mass, but begins in the cooler regions of the metal and proceeds in the opposite direction to the thermal cooling gradient. The solidification advances into the melt in all directions which are normal to its main axis of progression, so that a dendritic or tree-like pattern is formed. The secondary, tertiary and succeeding minor axes, all normal to their preceding members, fill out the spaces between adjacent dendrites until all the mass is solid. The dendritic growth of a crystal is shown in Fig. 1.

Grain formations which built up the dendrite may be subject to growth by recrystallization if two or more crystallites are nearly alike in orientation. Under favorable circumstances one assumes the same atomic ar-

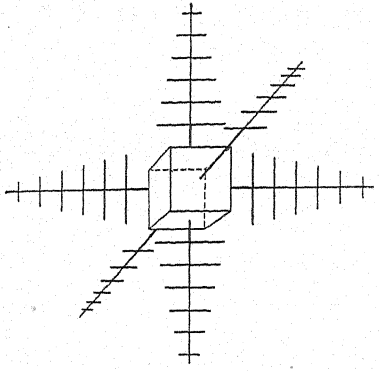


Fig. 1—Dendritic Growth of Crystal

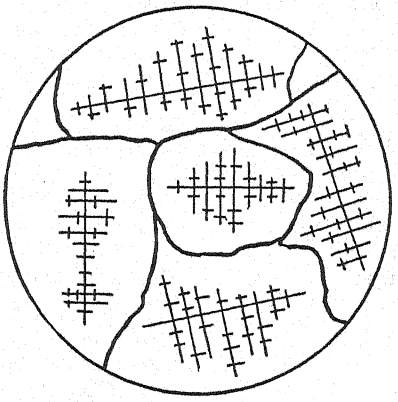


Fig. 2—Grain Formation from Individual Nuclei

rangement as the other and becomes part of it. Too rapid cooling, however, lowers the atomic mobilities which permit this crystal growth. High temperatures favor this action. The grain formation from individual nuclei is shown in Fig. 2.

Solid Phases from Molten Steel.—Solidification of alloys, such as steel, does not occur at a fixed temperature, but within a range. Initiation of solidification begins at the liquidus and is complete at the solidus temperature. The mixture of solid and liquid states extends over what is called the mushy stage. In mild steel the first metal to freeze is that of the purest composition, or unalloyed iron. On continued freezing this becomes more impure and contains increasingly larger amounts of the elements present in steel. In the phase diagram the first solid metal shown to appear is known as high-temperature ferrite or the delta ferrite. Its lower temperature equivalent, which will be discussed later, is alpha ferrite. The formation of the delta phase does not extend above 0.55% carbon content. Austenite forms on exceeding this figure.

Austenite, or the solid solution of iron carbide in gamma iron, is also of a variable composition, since the higher solubility of the residual liquid compared to the solid state concentrates the metalloids carbon, manganese, silicon, sulphur, phosphorus, etc., progressively in the parts last to freeze. However, diffusion in the solid state near the melting point accomplishes considerable equalization of the composition and particularly the carbon distribution. Below 1333°F. (723°C.) austenite of plain carbon steel is unstable on normal cooling and decomposes to ferrite and cementite. Beyond some 1.7% carbon the cementite of the composition Fe_3C, forms directly at the temperature of the solidus. This carbide does not appear directly from the melt, except when the carbon content is above 4.30%. Alloys which solidify to form carbide directly from the melt have industrial application in the form of white cast irons or hard surfacing metals to resist wear and abrasion.

Weld Metal Solidification and Segregation.—If molten steel solidifies upon a chilling surface, such as a mold or the base metal in a welding operation, there is formed immediately near this surface a thin, solid layer of practically the same composition as the liquid metal. The rapidity of solidifying prevents any great selective solidification with varying composition in the solute elements. However, the original melt composition in the case of added weld metal is modified by mixture with base metal which is fused by the heat of the welding process. The extent or penetration of this fusion and incorporation of either base metal or sublayer of added weld metal is a function of the electrode used, the arc current, rate of arc movement and all the factors concerned with heat transfer away from the arc vicinity.

The heat effect, measurable by the amount of fusion penetration and alloying, is important in respect to reaction of the liquid metal with the base metal. It is observable in respect to effect on "laminations," undercutting in the side walls of weld grooves, metal shrinkage and gas formation and the distortion in the assembled structure. Undercutting or the melting away of the side wall of the base metal is a frequent cause of slag entrapment in the undercut cavity.

In many welding processes the extreme rapidity of freezing of the added weld metal may approach the condition mentioned above where little preferential solidification can occur and the final composition is practically uniform. Heavier weld deposits with higher heat input permit more pronounced dendritic solidification and the amount of dendriticism is indicative of the solidification rate. The primary axes of these dendrites are relatively low in impurities, while the interdendritic interstices are most concentrated in metalloids. However, after the solidification, the migration of carbon and other elements effects equalization in some proportion to the individual diffusivities.

There is, in addition to dendritic segregation, a zonal effect evident as macropattern. In some heavy, single-pass welds this may be evident as a columnar structure with central zones of higher concentration of metalloids. This macrosegregation or gross variation of the dendritic effect may result from changes in heat transfer through outer solid layers, liquid convection, latent heat effects, liquid shrinkage gravitational influences and, in general, conditions established by size and form of the liquid mass. It is this macro effect which is usually described as "segregation," since the micro order of

dendritic segregation is not easily determined by chemical sampling. It is, however, discernible in its response to properly selective etchants on microscopic examination.

Gas Evolution and Shrinkage

Sometimes the concentration of soluble oxygen and carbon is sufficient on progressive segregation that these constituents react to form carbon monoxide. This may occur during solidification, despite the cooling temperatures, because of the mass action from increased concentrations of reactants in the residual liquid. The advancing wall of solidified metal aids this reaction by forming a nucleation surface. Because of the viscosity of the molten metal in the mushy state and confinement of the carbon monoxide evolution between dendrites, the gas bubbles do not escape and porosity is the result. Maintenance of a liquid pool on top of the metal mass helps to prevent such an entrapment.

The shrinkage of liquid metal on cooling is modified by a sudden increase at the moment of solidification. This may result in shrinkage cavities unless the metal flow from the residual melt can fill or feed the voids so formed. In the relatively thin deposit layers of ordinary multipass welds, solidification shrinkage is not a serious consideration. In heavy deposits, however, the shrinkage forces may effect a partition of the mushy metal, especially in the segregation zones, which freeze last. Such ruptures are known as "hot tears" because of the tearing action on weak but plastic material. Liberation of gas into the shrinkage cavity will increase its size and add to the danger of hot tears.

Although weld metal is often considered as having the characteristics of the ordinary metal casting, it differs markedly in several ways. First, the metal is usually added in successive layers which can be built up to heavy mass deposits. This, as we have mentioned, minimizes solidification shrinkage effects in the mushy stage as well as marked segregation phenomena. Rapid rates of cooling prevent the formation of a large grain size in the weld, and the annealing action from the superimposed beads can improve its fineness by recrystallization. Although gas reactions are aided by high liquid metal temperatures during welding, the escape of gases is made easier because of the small depth of the single weld deposit, and porosity from this source is less likely to occur. However, weld metal has other tendencies toward porosity typical of the welding method. Preheating, as used in welding has a more pronounced effect upon the weld metal than mold heating on cast materials, since heat is liberated from the base metal on cooling and the mass of the weld deposit is relatively small.

SOLID CONSTITUTIONAL RELATIONSHIPS IN PLAIN CARBON STEEL

Pure iron undergoes three allotropic transformations in cooling from the solidus to room temperatures. At the A_4 temperature of 2535°F. (1390°C.) the delta ferrite, first to solidify, is transformed to gamma iron or austenite. At 1670°F. (910° C.) the gamma phase changes to alpha ferrite. Both the delta and alpha phases crystallize with a body-centered cubic lattice. This crystallization results in an atomic packing with a representative unit

cell having atoms at all corners of the cube and one at the cell center. The gamma phase has a lattice arrangement with atoms at all corners of a cubic cell and in the center of all six faces. The crystal or grain consists of a parallel assembly of such cells in contiguous relationship (see Figs. 3 and 4).

The Iron Carbon Constitutional Diagram

The addition of carbon to iron results in a proportional shifting of these allotropic temperatures and lowering of the liquidus and solidus range. It likewise changes the composition of austenite and permits the forma-

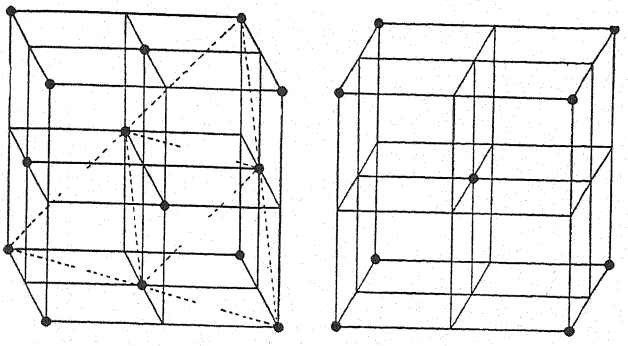


Fig. 3—Body-Centered Cubic and Face-Centered Cubic Lattices

(*a*) (Left) Face-Centered Cubic Crystal. (*b*) (Right) Body-Centered Cubic Crystal.

tion of iron carbide or cementite. The iron-carbon constitutional diagram is shown in Fig. 5. In this diagram practically complete equilibrium conditions are assumed in which sufficient time is given for essential completion of all reactions. The constitutional diagram does not indicate the transition products of the final phase change or the factor of time in heating or cooling.

In the reviewing of the solidification of steel it has been pointed out that in low carbon metals the delta phase is first to solidify but is converted to the gamma phase at only slightly lower temperatures. At higher carbon contents the gamma iron forms directly from the liquid phase. The gamma constituent is a solid solution of carbon or iron carbide in gamma iron and at lower temperatures it precipitates the carbon either as pearlite or in the free condition. Below some 0.83% carbon, ferrite is precipitated from solid solution before the cementite is rejected, and the temperatures at which this begins are indicated in the A_3 line. Since ferrite has very little solubility for carbon, the concentration of this element is increased in the remaining untransformed austenite. When this concentration reaches 0.83%, which is the eutectoid composition, there is a simultaneous precipitation of ferrite and carbide below 1333°F. (723°C.) in a characteristic and intimate arrangement known as pearlite.

If the eutectoid composition is exceeded, iron carbide is the first phase to precipitate from austenite. At the lower limit of its solubility at the A_1 temperature the remaining austenite is converted to pearlite.

The eutectic of austenite and cementite, which is characteristic of cast iron, is formed from compositions of higher carbon contents. At lower temperatures the final constituents are cementite, pearlite and ferrite, and in the presence of high silicon and slow cooling rates the cementite may decompose to graphite. In all of these alloys a small but measurable solu

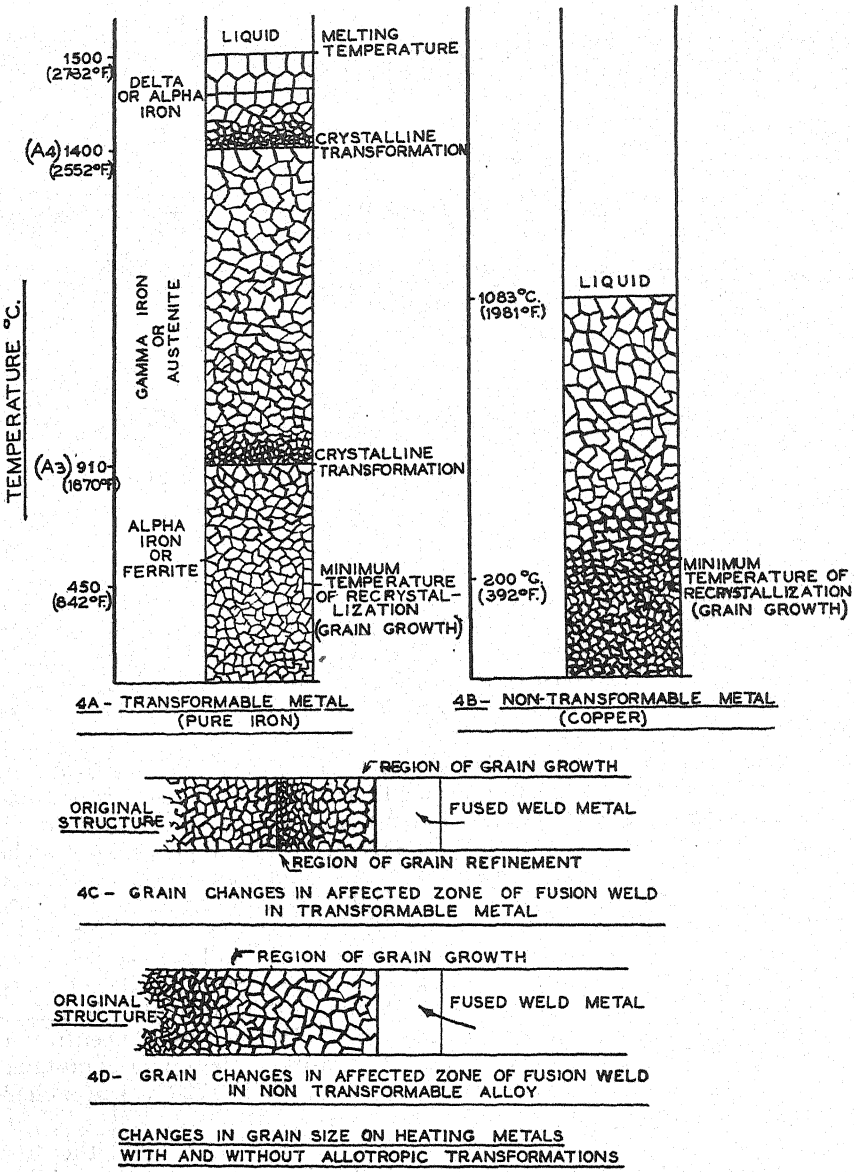


Fig. 4—The Effect of Allotropic Transformations in the Heating of Steel

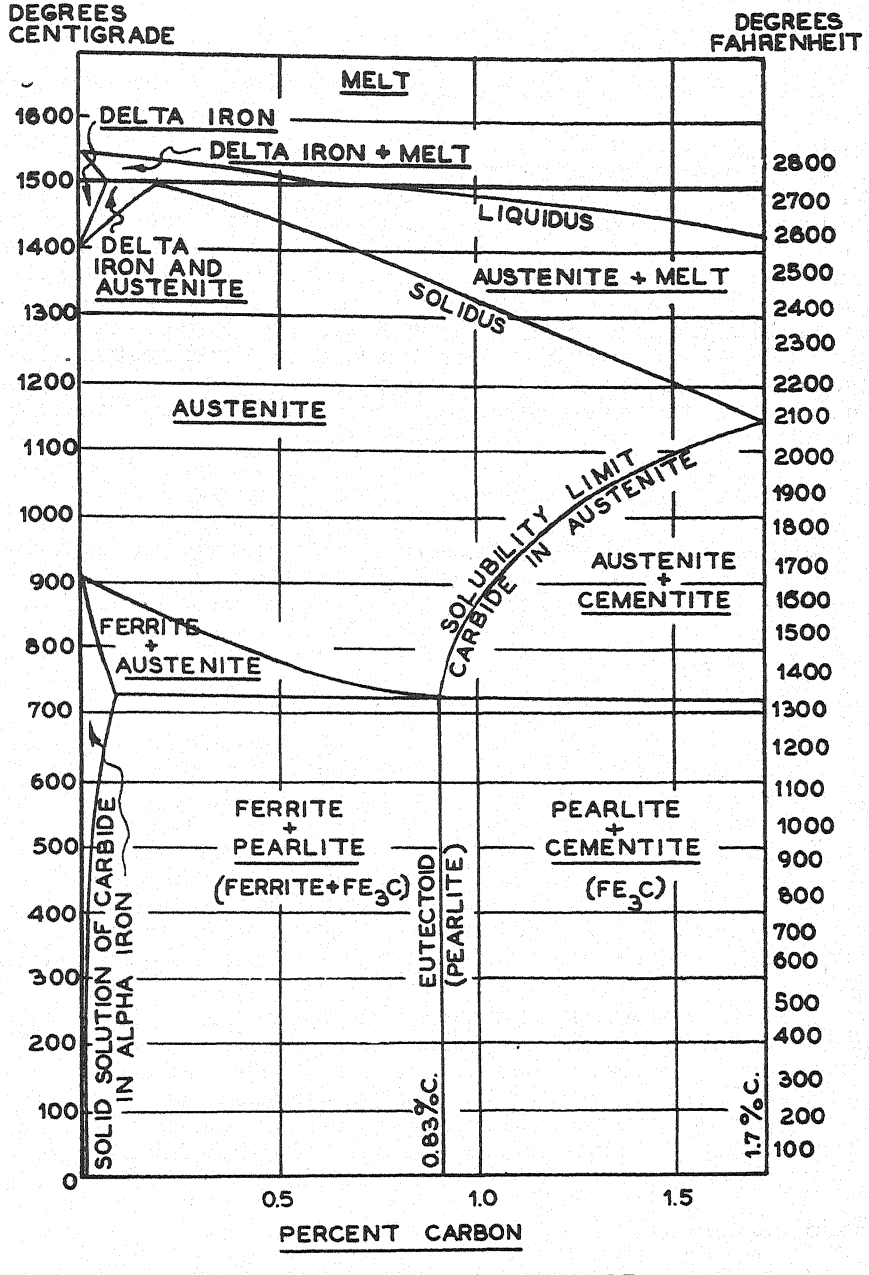


Fig. 5—The Iron-Carbon Constitutional Diagram

bility for carbon in ferrite is realized which has a maximum of only 0.03% at room temperatures.

Recrystallization

The allotropic transformations in steel not only cause a rearrangement of the atomic pattern, but are accompanied by recrystallization, since the transformation process initiates simultaneously from a large number of nuclei and proceeds until interrupted by adjacent recrystallized grains. Grain refinement is ordinarily accomplished in industrial practices by heating steel to just above the A_3 temperatures, which assures that all of the ferrite is transformed and recrystallized. If the temperature is carried much above the A_3 limit and well into the completely austenitic region, the grain size increases by growth in which the members assume the same crystal orientation as a neighbor and become as one. Growth differs from recrystallization in that it is independent of phase transformation, since the same atomic arrangement is maintained. It implies an effect similar to a crystal rotation so that grains of the same lattice spacings also assume the same crystallographic axes in adjoining grains.

In plain carbon steel weld structures of low carbon contents we rarely find austenite in either the added or base metals, since this phase transforms rapidly during cooling and is retained metastably only by exceedingly drastic quenching. However, the transformation products from austenite have a very large possible diversity, which depends on their stage of aggregation as controlled by the cooling rate. For this reason, although the constitutional diagram shows the stable association of phases, it does not fully represent the products of the various thermal treatments which govern the solid state reactions in weld metal or in the base material affected by the welding heat.

The results of grain refinement by recrystallization and those of grain growth at elevated temperatures are nicely illustrated in the welding process. For example, the moderately coarse "as solidified" structures of weld deposits can be refined by a superimposed layer of weld metal which carries the temperature of the underlying bead just above the upper critical temperature or A_3. The chilling action of the thermally conductive base metal prevents excessive temperatures and grain growth which is impossible at this fairly rapid rate of cooling. However, in some weld zones the temperatures may reach values well above the A_3 limit and grain growth results therefrom.

Base metals are generally of higher carbon content than the added weld metal, and, therefore, their recrystallization occurs at somewhat lower A_3 temperatures. Frequently the microstructure of the heat-affected areas in a single weldment shows both an area of grain refinement and also a very evident growth. The thermal histories which are revealed by these structural modifications are reflections of the heat effect of the welding technique and the heat balance as affected by the physical dimensions of the structure.

Solid Solubility

Among the elements common to steel, silicon and phosphorus are most soluble in alpha or delta ferrite and further its formation, while carbon, manganese, nitrogen and oxygen have a higher solubility in austenite or

gamma iron and extend the temperature range in which it can exist. The solubility differences of elements in the two phases are evident in commercial steels, by segregation and precipitation from solid solution. The amount of solute influences its state of aggregation and distribution in its precipitated form. Of the elements mentioned, carbon is by far the most responsive to solubility differences. Manganese and silicon are not present in amounts which even approach their maximum solubility in alpha or gamma phase. The usually restricted amounts of nitrogen and oxygen minimize the importance of their changes in solid solubility. Nevertheless, in low carbon weld metals the contribution of the last two elements to the mechanical properties may be more evident, as the carbon is less effective.

Within the transformation region between the temperature demarcation lines of A_3 and A_1, the alpha and gamma phases coexist in proportions which vary with temperature. In cooling, the formation of alpha ferrite is attended by an absorption and enrichment of carbon in the untransformed austenite. Such elements as phosphorus and silicon have less solubility in the austenite and tend to dissolve in the ferrite. Some practical effect of these tendencies is seen in a mechanical segregation of carbon in the pearlite derived from austenite if hot working and particularly hot-rolling processes are continued below the A_3 temperature range. The difference in plastic properties between ferrite and austenite results in their parallel alignment along the axis of extension. This effect is known as banding. The structure is illustrated in Fig. 6.

The occurrence of banding is furthered by continuing the working process to below the A_1 temperature. The differential plasticity of ferrite and pearlite results in a striated or banded structure. Elements promoting an equal proportion of both alpha and gamma phases in the A_3 A_1 transformation region favor the occurrence of banding, while carbon contents which make the mixture predominantly austenitic tend to minimize the effect. Base metals utilized for welding and consisting of banded steels may show a local intensification of carbon oxidation on fusion with the added weld metal at the regions of the pearlitic bands or segregates. In weld rods, banded segregation of a serious order can result in uneven melting and frothing.

Precipitation from Solid Solution

Precipitation of carbon as iron carbide from austenite can be modified to give an extensive diversity of final structures. This may be accomplished by drastic quenching to preserve the austenitic or martensitic state metastably, then tempering or regulating the austenite decomposition under isothermal time-temperature conditions. A less definite, but frequently the only expedient, method of attaining the desired constituent products is to control the rate of cooling from the austenite range or the A_3 temperature. The addition of alloy elements also influences the stability of the austenite and may lower its rate of transformation and, if this is not too sluggish, increases the ease with which the transformation reactions can be consistently controlled. Since the kinetics of the transformation process are so important and involved, a separate section will be given to its consideration.

The precipitation of elements of low concentration in steel such as nitro-

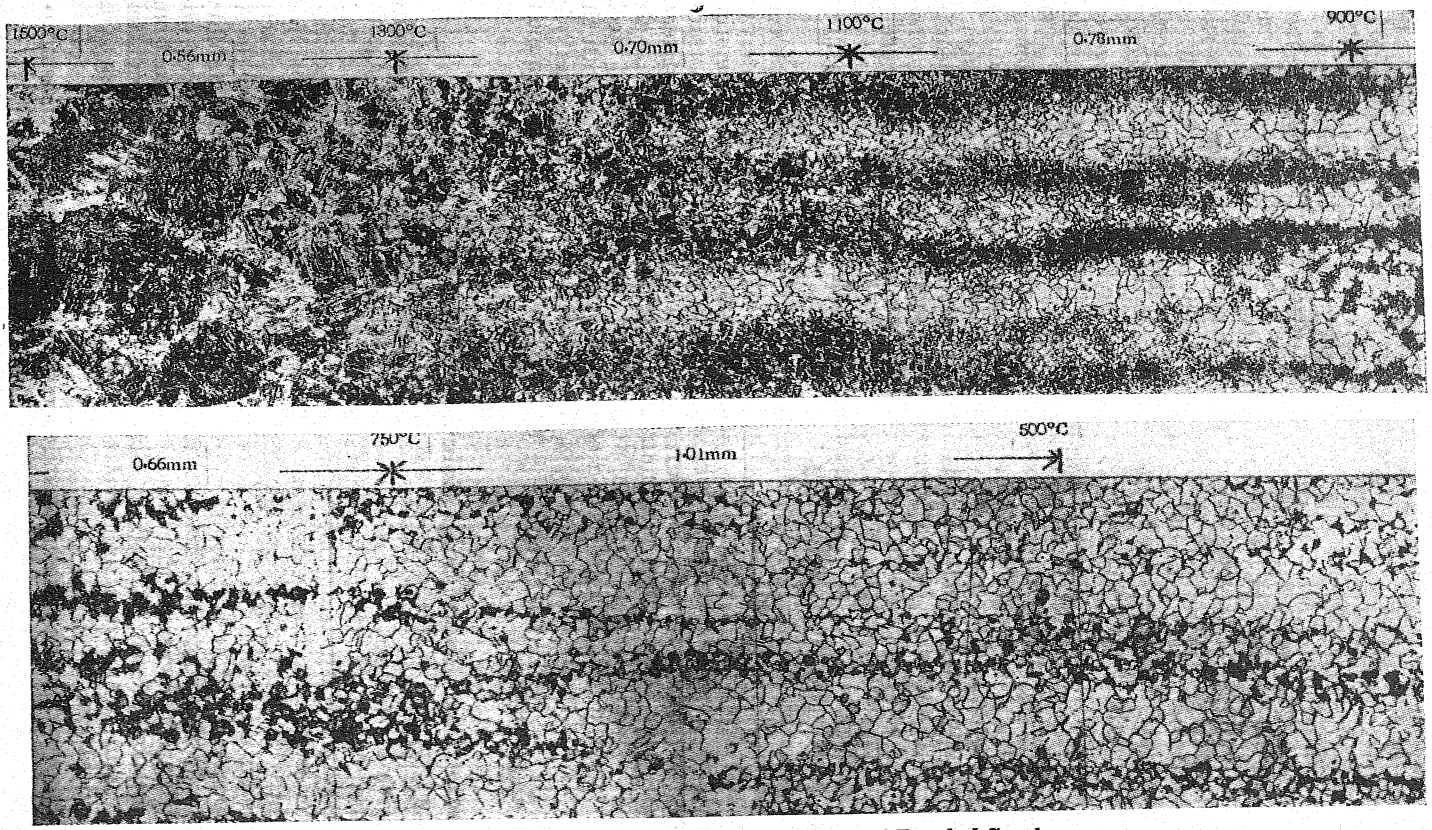


Fig. 6—The Microscopic Appearance of Banded Steel

gen and oxygen does not show an abrupt solubility change at the phase transformation temperatures. Both of these elements, and carbon as well, show a minor solubility in alpha iron. This solubility decreases with only a moderate gradient as the temperature drops below the A_1. The relatively slow diffusion and coalescing rate at these lower temperatures and the small concentrations involved result in a slow precipitation of wide scattering and often of submicroscopic size. By raising the temperature and increasing the time period, a coalescence of the precipitated phase may be obtained to the point that microscopic identification is possible.

The highly dispersed nature of precipitation from solid solution well below the subcritical temperatures results in an effective hardening and strengthening action upon the metallic matrix. This has been likened to a keying action on potential lines of shear or slip under stress, which locks planes of plastic movement within each grain or crystal. The order of dispersion and size of the precipitated particles, which is most effective in the strengthening action, is known as "critical dispersion."

On rapid or even moderately rapid cooling, the elements of low solubility in ferrite are frequently metastably retained in solid solution. On standing at room temperatures, a strengthening of the matrix is gradually accomplished as precipitation slowly proceeds even at these low temperatures. This process is called age hardening. If the steel is heated slightly above room temperatures, the aging is accomplished more rapidly and is indicated as accelerated aging. It is also promoted by stressing the material, and this effect plus that of cold working is known as strain aging. If, however, the aging temperature is too high, coalescence of the dispersed phase occurs and the strengthening effect is less pronounced. There is evidence to indicate that aging or subcritical precipitation contributes much to the properties found in weld metal which is otherwise not strictly explainable on the basis of the effect of carbon in the transformation products from the gamma solid solution. Certainly the properties of weld metal are not fully comparable to ordinary cast materials of similar composition in the elements commonly reported for analysis. The high temperature of fusion and other thermal effects are believed to be responsible for this difference in properties in the solid state.

AUSTENITE TRANSFORMATION IN PLAIN CARBON STEEL

The transformation products from the decomposition of austenite in plain carbon steel can vary widely in microstructure and in the mechanical properties that they confer on the steel in accordance with the time rate of cooling from above the A_3 temperature and the dwell at any specific temperature. Rapid and drastic quenching procedures result in the formation of a hard, brittle microstructure known as martensite and the tendency toward its formation increases strikingly with carbon content.

On cooling from above the A_3 temperature at progressively lower cooling rates, a limiting critical rate for martensite formation is reached, beyond which slower cooling permits the formation of pearlite in its stead. The pearlite structure develops from a simultaneous precipitation of cementite and ferrite in a lamellar and parallel array. The coarseness or the width of the carbide and ferrite lamellae increases with slower cooling rates.

At more rapid rates the separate constituents of this association are microscopically resolvable only under high magnification, so intimate is their assembly.

Method of Heat Treatment

Slow cooling from above the upper critical or A_3 limit is known as full annealing. This usually gives the ductile properties characteristic of the presence of coarser pearlitic aggregates. Normalizing or cooling in still air results in finer structures and improved toughness. A release of internal stresses from mechanical treatment or differential thermal expansion also accompanies annealing, since the thermal energy and necessary time for plastic readjustment of these stresses are afforded by this treatment.

If rapid quenching to room temperatures or normalizing is followed by a supplementary heat treatment under the lower critical or A_1 temperature, modification of the martensite or quench structures can be accomplished. A heat treatment consisting of reheating to just below the A_1 temperature, holding for a period of time, followed by slow cooling to room temperatures is known as process annealing. This results in a microstructure in which the carbides tend to assume globular form within the ferritic matrix. If the holding is appreciably prolonged, the carbide particles coalesce into larger globules. This longer treatment imparts to the structure the maximum softness and is known as spheroidization.

A reheating of quenched steels at lower isothermal temperatures under the A_1 limit is known as tempering. The higher tempering temperatures permit nearly complete dissociation of the carbide and ferrite phase, while the lower temperatures produce more compact and nodular aggregations. While all of these modification products from martensite are essentially aggregates of ferrite and cementite, there is an appreciable difference in their microscopic appearance. In the sequence of higher to lower tempering temperatures and according to the intimacy of the assembly of the two phases, we can differentiate between the spheroidized structure of completely tempered martensite, troostite and sorbite. At relatively low tempering temperatures martensite prevails practically unmodified and if any residual austenite should be retained from quenching, its final decomposition results in this constituent.

To some extent, a longer time period of tempering at lower temperatures may correspond in effect to shorter periods at higher temperatures. However, the relationship is not strict. Both increased temperature and time of holding in this treatment helps to eliminate internal stresses. Cooling from tempering temperatures may be conducted in air or other coolants. Slow cooling from certain tempering temperatures may cause a type of embrittlement, which will be discussed later.

Pearlite is a characteristic constituent in most non-austenitic base metals employed in welding. Low carbon weld metals, however, contain a ferrite-carbide aggregate of related but dissimilar assembly suggesting local regions of finely spheroidized cementite but still in close aggregation.

Products of Austenite Transformation

For most practical purposes the austenitic decomposition products of

interest in industrial practices are martensite, pearlite, ferrite and cementite. Martensite is generally accepted as a transitional product from the gamma-alpha transformation. It has a tetragonal lattice and can be represented by a strained alpha ferrite supersaturated with carbide of ultramicroscopic fineness. Its microstructural appearance is acicular or needle-like on the etched surface of polished specimens. It is exceedingly hard and brittle.

In the high temperature transformation of hyper-eutectoid steels, which contain over 0.83% carbon, cementite is rejected from austenite until the carbon content of austenite is reduced to that of the eutectoid composition, which then transforms spontaneously to pearlite. Hypo-eutectoid steels, of lower carbon content than 0.83%, undergo an austenite decomposition with the rejection of ferrite. When the carbon concentration is that of a eutectoid composition spontaneous formation of pearlite results throughout. In welding operations it is the hypo-eutectoid steel base or weld metal with which we will be most concerned.

The rate at which hard martensite just forms from austenite with no or very little formation of pearlite is known as the critical cooling rate. Measured in degrees per hour, for a hypo-eutectoid steel the critical rate decreases with higher carbon content and larger initial grain size when quenched from a fixed temperature above the A_3 range. The comparative ability of the steel to harden is known as hardenability and is measured by the maximum obtainable hardness and the slope of the hardness gradient across a standard quenched specimen of such a thickness that some incompletely hardened core persists.

Isothermal Transformation

The importance of the isothermal transformation rate of steel is that it provides a useful measure of relative rates of cooling or prolonging of post heat treatment required to prevent embrittlement from welding heat temperatures.

Austenite decomposition is furthered by decreasing the cooling rate from above the upper critical temperature or alternately by subjecting the retained austenite to an isothermal heat treatment below the lower critical temperature range. Studies of the progression of this decomposition with time at various temperatures show that the relationship is not continuously proportional to temperature, but changes in accordance with an S-curve. Figure 7 shows the transformation rates for a carbon steel of eutectoid composition. Examination reveals that the most rapid transformation occurs at some 950°F. (510°C.), while just below 1350°F. (732°C.) or when approaching lower temperatures the time required for complete transformation is quite prolonged.

The time required for austenitic decomposition to begin is regarded as the period necessary for nucleation. Some investigators have chosen the time required to complete one-half of the transformation for comparing this process in different steels. Since the time to reach completion after once initiated has been found to vary with the microheterogeneity, this period may differ.

Retained austenite in hyper-eutectoid steels which have been cooled isothermally to temperatures just below the lower critical range begins to

transform earlier than in lower carbon steel. This is attributed to the nucleation effect of the pro-eutectoid carbide which is precipitated ahead of the pearlite. At lower temperatures, such as above 400 to 700°F. (204 to 371°C.) the maximum transformation rate decreases in the sequence of hypo-eutectoid, eutectoid and hyper-eutectoid composition. The transformation usually initiates at the grain boundaries and the fine-grained metal transforms more rapidly than coarse grained, since it contains a larger proportion of boundary material. The relative transformation rates are of the order of two to one.

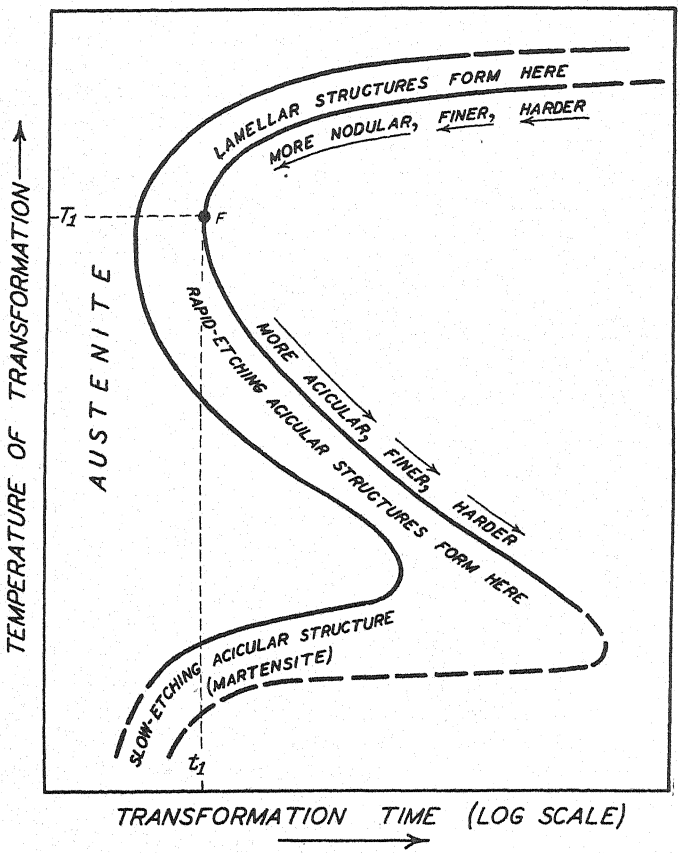


Fig. 7—The Idealized S-Curve for 0.8% Carbon Steel Depicting the General Relation Between Transformation Temperature and Nature of the Product

If the isothermal transformation of steel is conducted near but below the A_1 temperature, the product is a coarsely lamellar pearlite. At progressively lower temperatures this product becomes a finer and more nodular pearlite. At still lower temperatures the hard and brittle, acicular martensite appears. An intermediate product of somewhat similar ap-

pearance and of high hardness, but without the intense brittleness of martensite, can be obtained by isothermal treatment within 400 to 800°F. (205 to 425°C.). This is known as bainite.

Relationship of Isothermal and Cooling Transformation Rates

In many industrial applications, such as welding, there is the greatest concern about the effect of cooling rate upon the transformation reaction. Consequently, attention has been given to relating this cooling to the formations obtainable in accordance with the S-curve. At the present time this method is only applicable to base metals.

Figure 8 shows various cooling curves of different slopes superimposed upon the isothermal or S-diagram. The safe rates of continuous cooling which permit the formation of fully lamellar pearlite structures by intersection with the zone of pearlite occurrence are represented in Curves A, B and C. Faster rates than that of Curve C intersect the lower part of the S-curve where transformation to martensite takes place at around 400°F.

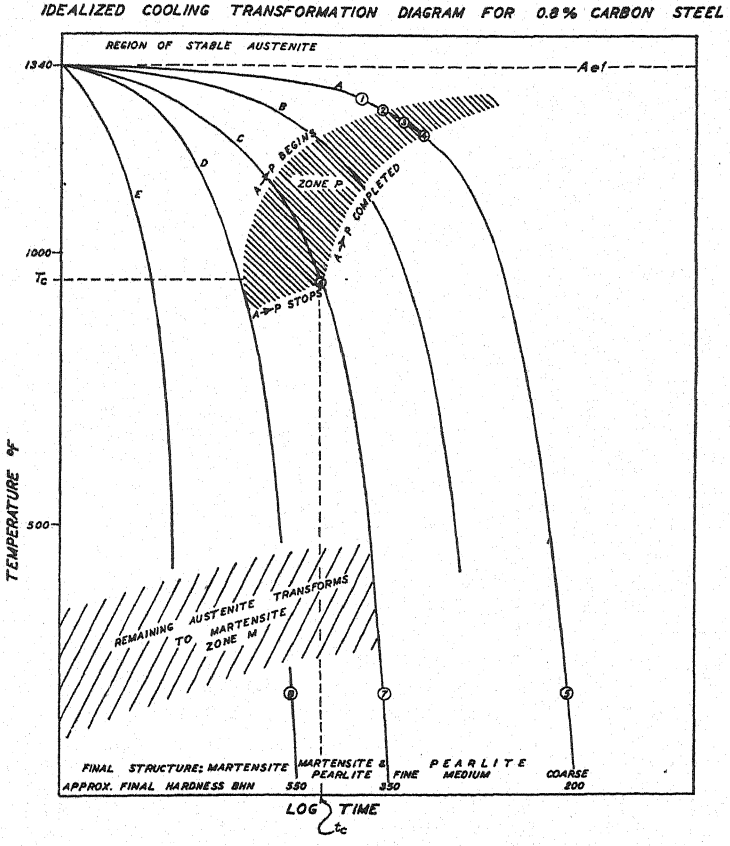


Fig. 8—The Idealized Cooling Transformation Diagram for 0.8% Carbon Steel

(205°C.). Rates between C and D result in the occurrence of both pearlite and martensite. The critical cooling rate for safe welding is that of C.

The S-curve has been utilized by Aborn as a possible means for the estimation of a maximum safe cooling rate for a steel of known isothermal behavior.

Since the pearlitic transformation products of austenite occur only below the critical temperature A_1, and since their formation ends at the completion edge of the pearlitic zone of Figure 8, these temperature limits indicate the temperature range in which the time of dwell is especially important. Actually there is always a downward displacement of the transformation temperature on cooling, so a correction of 100° is applied at the completion edge of the isothermal diagram (Fig. 7).

The maximum safe cooling rate is attainable at the temperature which permits the most rapid isothermal transformation. This is that of the upper nose of the S-curve at around 950°F. (510°C.). The cooling period permitting the maximum rate is determined by multiplying the isothermal period by 1.5. This multiple has been empirically determined as the correction for displacement caused by the 100°F. lowering on cooling. Consequently, for coarse-grained material, which transforms most slowly, we have:

$$r = \frac{T_0 - (T_1 - 100)}{1.5t_2}$$

where T_0 = temperature (in °F.) of the transformation of austenite to ferrite plus carbide at the equilibrium (Ae_1).

T_1 = temperature (in °F.) at which isothermal transformation is completed in minimum time t_2.

t_2 = time interval required for completion of the isothermal transformation of coarse-grained austenite at the temperature T_1.

r = maximum safe cooling rate with transformation of course grained austenite to lamellar pearlite without martensite formation.

The more rapid transformation accompanying fine-grained structures requires a faster rate of cooling for its suppression. This is expressed by the relationship:

$$r = \frac{T_0 - (T_1 - 100)}{3t_1}$$

where t_1 = time interval required for completion of the isothermal transformation of fine-grained austenite at the temperature T_1.

There are some very sluggish alloy steels which do not transform on cooling except at inordinately slow rates. However, the transformation to structures of requisite toughness may be completed at or somewhat above 650°F. (343°C.) on applying auxiliary heat to restrain the cooling. Empirically it has been found that a safe cooling rate is obtained by tripling the time required for transformation at 650°F. (343°C.), as shown on the isothermal diagram. Experimental data have demonstrated that the austenitic grain size is not a significant factor at this temperature and no adjustment for it need be made.

Effect of Cooling Rates on Weld Metal

A single weldment or welded construction involves a thermal history of great variety resulting from different rates of cooling of molten weld metal and from the subsequent heat treatment. Ordinarily the carbon content of plain carbon steel weld metal is so restricted that no martensitic structures can form at normal rates of cooling from welding temperatures, despite the chilling effect of the base metal. If the rate of deposition of low carbon weld metal and the heat input are such as to result in slow cooling of the weldment, there is obtained a coarse-grained columnar structure with the carbide precipitated in finely divided bodies along the grain boundaries. The columnar form of the grain is due to a preferred axis of growth on solidification from the chilled surface toward the weld center.

The shallower depositions of the multipass welds are subject to recrystallization from the heat of overlayers with the establishment of a finer and equi-axed grain, but the carbides are still found in the grain boundary in a fine globular form. If the carbon content of the weld metal is increased, the character of the cementite aggregation in the ferrite approaches more nearly the form recognized as pearlite. At still higher carbon contents the carbides are assembled into more compact aggregates.

Heat-Affected Zones in Welded Base Metal

The heat-affected regions of welded base metal may conveniently be described as the fused zone, the zone of grain coarsening, the zone of grain refinement and the zone of spheroidization near the heat-unaffected material. The zone immediately adjacent to the weld metal is that part which has been heated to the melting point and combines some of the properties of the weld metal and unfused base metal.

The grain-coarsened zone is most likely to contain the brittle structures of martensite if the carbon content is sufficiently high, since it has been heated well above the A_3 temperature into the austenitic region from which the cooling has been moderately rapid. The unfortunate coincidence of coarse and brittle structures may be reflected in a low ductility, unless a softening heat treatment is accorded.

The zone of grain refinement is one in which the effect of welding heat has carried the temperature just above the A_3 critical range and the cooling has been moderate. The adjacent or spheroidization zone grades from the condition of grain refinement to one of subcritical tempering action on the base metal. Part of this zone exhibits ferrite and spheroidized pearlite in a graduated range which shows the particle size and degree of dispersion of the carbide decreasing as the unaffected base metal is approached. The second part of this zone may have experienced some tempering action without noticeable changes in microstructure. Usually this consists merely of a slight softening or stress-relieving effect, but some compositions, and certain alloy steels in particular, are sensitive to a temper embrittlement. This is a moderate hardening and embrittling effect which is obtained on slow cooling from a temperature range of some 400 to 600°F. (204 to 316°C.). The effect is eliminated by moderate or rapid cooling from above this range.

Differences in Cooling from Welding Heat

The conditions which favor a non-brittle base metal as welded include a low carbon content and fine grain size. Base metals are commonly limited to 0.35% carbon or less, depending on other contributing factors. Heavy sections increase the hardening and chilling effect. Small or intermittent weld deposits may be undesirable, where they have insufficient welding heat for proper self-annealing action. For a similar reason the base metal affected by the first bead is more liable to martensite formation, since the welding heat is not sufficient to permit a slow cooling rate in the heat-affected zone. In general, a sharp and well-defined heat-affected zone is the result of a steep temperature gradient from weld to base metal. A wider zone with a more gradual change in structure is obtained by a slow cooling rate by preheating the base metal.

Preheating is advantageous to lower the cooling rate of the heat-affected zone. After the welding operation is started the heat from the arc or flame source should be sufficient to maintain the annealing action. The metallic arc process supplies a high heat intensity, but gas welding is frequently more convenient for manipulation of the heat and its distribution over parts adjacent to the weld. This is because of the wider metal contact with the hot expanded gases. The heat transmitting characteristics of the electrode as determined by its type, polarity, rate of welding and rod diameter are significant in their effect on the restrained cooling of the base metal. Post annealing from an auxiliary heat source is sometimes required for satisfactory properties. Some efforts have been made to determine the effect of mass, thickness of section and effect of the geometry of the edges to be joined upon the heat transfer in the base metal. It would be most useful if a quantitative value for heat and temperature characteristics could be readily obtained in order to foretell the required thermal treatment of the affected parts. The ratio of the weld metal volume to the area of the fusion surface, however, provides an approximate measure of this heat flow.

CONSTITUTIONAL RELATIONSHIPS AND THE AUSTENITIC TRANSFORMATION IN ALLOY STEEL

The influence of specifically added alloy elements to otherwise plain carbon steel is especially important if the steel is to be welded. Alloy elements not only can improve the final properties of the steel in the weld and base metal, but control the rate of the austenitic transformation in the heat-affected section during and following the welding process. On cooling to room temperature, the nature of the transformation products determines the capacity of the steel to withstand the severe thermal stresses that are induced. A sufficiently soft and ductile metal structure can relax these stresses. Strong and brittle microstructures, such as those of martensite, either retain the thermal stresses without plastic adaptation to these forces or release them by cracking and rupture.

The effect of alloy elements on the thermal response to temperatures from the welding heat can be divided into two types, frequently but not necessarily related to each other. The first is indicated in its modifica-

tion of the iron carbon diagram under essentially equilibrium conditions. Most significant in these modifications is the ability of some elements to change the temperature range over which either austenite or ferrite can exist in a stable form. Alloy elements may also change the capacity of the steel to form and retain iron carbide or complex carbides.

The effect of elements which promote the formation and retention of austenite even at temperatures well below the usual transformation limit of plain carbon steel is illustrated in Fig. 9. For convenience, the effect of

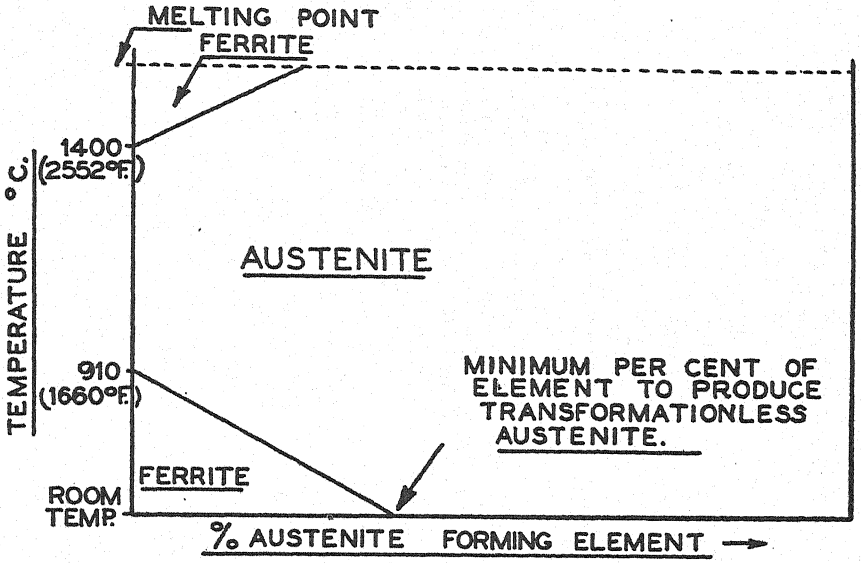


Fig. 9—General Effect of the Presence of Austenite-Forming Elements in Solid Solution with Iron

carbon is not included. Figure 10 shows a type diagram for alloy elements which are ferrite-promoting over an extended temperature region.

The second important effect of alloy elements in steel is essentially one of kinetics or particularly the rate of transformation of austenite during cooling to the stable products of a lower temperature. Time for complete transformation may vary from seconds to days at certain temperatures. Where a prolonged cooling period is impractical because of economics or methods of fabrication, the ductile structures of full transformation may not be obtained. An excessively fast rate, on the other hand, does not permit good control of the structural products from austenite transformation.

Ferritic and Pearlitic Steels

Elements which are classed as ferrite-stabilizing are listed in Table 2. Common commercial steels of ferritic character which show minor, if any, formation of austenite at elevated temperatures are exemplified by the 4% silicon transformer steel and the 16 to 30% straight chromium low carbon

Table 2—Some Effects of Some Alloying Elements in Steel

Stabilization of Austenite	Hardening Tendency on Transformation	Carbide Formation	Restriction of Grain Growth	Stabilization of Ferrite	Strengthening of Ferrite
Nickel	Carbon	Vanadium	Aluminum	Chromium	Manganese
Manganese	Molybdenum	Titanium	Vanadium	Molybdenum	Silicon
Nitrogen	Chromium	Columbium	Titanium	Phosphorus	Phosphorus
Carbon	Manganese	Tantalum	Zirconium	Tungsten	Cobalt
Copper	Nickel	Tungsten	Nitrogen	Vanadium	Nickel
	Tungsten	Molybdenum		Silicon	Aluminum
	Vanadium	Chromium		Aluminum	Chromium
		Manganese		Titanium	Molybdenum
				Zirconium	Tungsten
					Nitrogen
					Copper
					Vanadium
					Oxygen

steel used for corrosion and heat-resisting purposes. Fully ferritic steels do not show an austenitic transformation and, therefore, cannot undergo grain refinement by such recrystallization. On heating to elevated temperatures, grain growth can proceed uninterrupted. Commercial steels of the ferritic type sometimes contain additions of austenite-forming elements to permit partial grain refinement by suitable heat treatment. Nickel, nitrogen and carbon are useful in this respect.

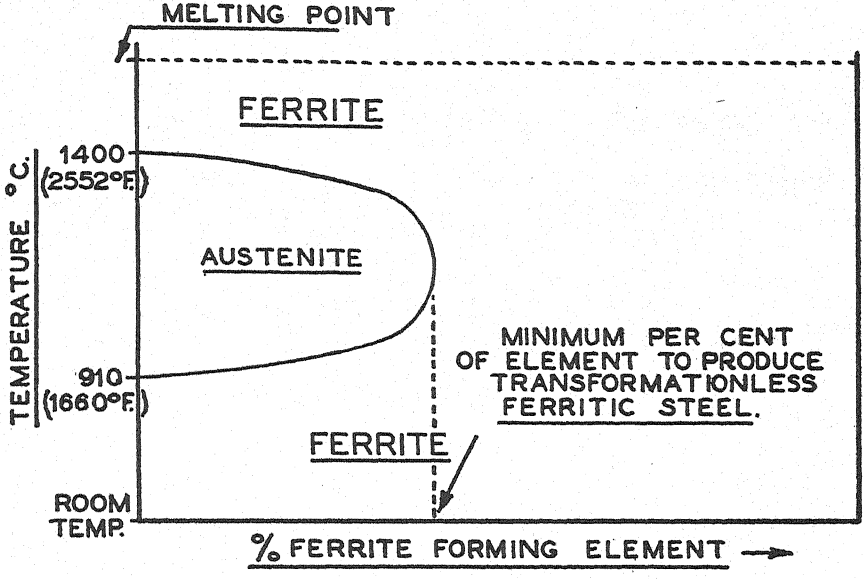


Fig. 10—General Effect of the Presence of Ferrite-Forming Elements in Solid Solution with Iron

The ferrite stabilizing tendency shown in the constitutional relationships is usually insufficient in most industrial alloy steels to prevent completely the formation of austenite. On cooling, moderate contents of ferritic elements in steel usually do not accelerate the transformation of austenite, but, in fact, may cause it to be exceedingly sluggish. Molybdenum and chromium, although ferrite stabilizing, constitutionally actually delay the austenite transformation when present in moderate proportions. Unless such alloy steels are low in carbon or are cooled very slowly, martensite forms in preference to ferrite, pearlite or other ductile ferrite-cementite aggregates.

For the most part alloy steels of the greatest usefulness as base metals in welded construction are the pearlitic types. These commonly contain low to moderate alloy elements and only sufficient carbon so that nodular to lamellar pearlite forms on natural or slightly delayed cooling from the welding heat. Corresponding weld metals may show the carbide in spheroided form. If the alloying additions are more extended, the steel may approach the martensitic types because of their kinetic sluggishness.

Austenitic Steels

Elements promoting the stable formation of austenite in steel are listed in Table 2. Carbon is very effective in forming austenite, but its limited solubility makes it necessary to add nickel or manganese for full phase stabilization. Nitrogen may be used to replace carbon in some applications. For economic reasons only sufficient alloying elements are added to austenitic steels to make the material stable under the expected conditions of service.

When utilized at room temperatures, the kinetic energy in the austenitic steel is insufficient to permit transformation, even over an indefinitely long period of time. At certain elevated temperatures, however, and over long exposures, some decomposition may occur, especially if the steel contains some ferritic elements, such as chromium, molybdenum or silicon, improperly balanced in respect to other elements of its composition.

In the corrosion and heat-resisting steels of the 18% chromium and 8% nickel series and their type variations,* instability of the austenite phase is observed at particular temperatures. Even a short time at the temperature range of about 900 to 1400°F. (482 to 760° C.) may result in intergranular precipitation of carbides. At still higher temperatures the precipitation is less selective and can occur within the grain. At lower temperatures precipitation may occur along unhealed shear planes produced by mechanical work. As the temperatures approach 1900°F. (1038°C.) solution of the carbides occurs and may be complete on holding at this level.

Exposure to 1600°F. (871°C.) and below with compositions of lower carbon and higher chromium, nickel, silicon, molybdenum or other elements than the 18–8 type may permit the formation of a brittle sigma phase. This forms from ferrite with the approximate composition of the intermetallic compound Fe Cr. Such changes in the austenitic alloy are significant in prolonged high-temperature service and even during the shorter time periods of welding-heat exposure. A properly balanced composition is consequently necessary to prevent the formation of the sigma phase.

Except for manganese, all of the elements listed in Table 2 as carbide forming are also ferrite stabilizing. Where they form highly stable carbides not easily soluble in austenite, even at high temperatures, they tie up some of the carbon and prevent its contribution to the austenite formation. Elements such as columbium, titanium, vanadium and tantalum are of this description. Their carbides are slow to diffuse, coalesce or dissolve in the austenitic solid solution.

The grain boundary carbide precipitation at 900 to 1400°F. (482 to 760°C.) is undesirable because it permits a localization of corrosive attack and consequent embrittlement in media normally not severely corrosive to steels of the 18–8 or more highly alloyed types. The addition of columbium to form columbium carbides can restrict this intergranular localization by its previous precipitation within the grains and by allowing only sluggish diffusion toward the grain boundaries. It also retains its full corrosion resistance.

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* Alloys of 18 Cr–8 Ni with Mo; 20 Cr–10 Ni; 25 Cr–12 Ni, and 25 Cr–20 Ni, may be regarded as modifications of the general type having the well-known 18 Cr–8 Ni composition.

Constitutional Effects of Alloy Elements in Welding

The constitutional tendencies of elements on ferrite, austenite or carbides are also significant when alloy steels are used in welding operations, either as base material or added weld metal. The unrestrained grain growth on the heating of fully ferritic steels to high temperatures during welding may result in embrittlement. Consequently, the high chromium steels of definitely ferritic tendency can sometimes be improved by the addition of some 2 to 3% nickel or .15 N or both. This insures a partial transformation and improves their strength and toughness. The brittle character of coarse-grain ferritic steels should always be considered in respect to the thermal stresses of welding and the precautions which must be observed during this process.

Austenitic alloys have important applications in welded construction, both as base material and as added weld metal. Weldable steels of the 18–8 type are frequently limited to 0.07 to 0.10% carbon in order to minimize intergranular carbide precipitation from the welding heat. The time dwell within the susceptible temperature range will vary with the means, technique and extent of welding, as well as the thickness of the members to be joined.

Titanium and columbium added to the 18–8 base metal have the advantage of eliminating sensitivity to intergranular precipitation. Their useful contents are usually four to ten times that of carbon. In added weld metals titanium is too easily oxidized during welding for effective use. Columbium does not have this objection and is employed almost universally for this purpose.

Austenitic weld metals have a special usefulness where it is important that the weld remain soft and ductile by undergoing no transformation to brittle martensitic structures. To maintain a superior austenitic stability the 25% chromium–20% nickel or the 25% chromium–12% nickel compositions are preferred to the 18–8 alloy. Not only does the weld metal remain ductile, but the lower fusion temperature of the 25–20 alloy, compared to lower alloy steels, results in a correspondingly smaller heating effect and hence narrower hardened zone in the adjacent base metal. Since the admixture with base metal is not extensive, the austenite is usually not diluted to an extent that it becomes unstable. Besides improved stability, the 25–20 alloy offers additional advantage to the 18–8 because its thermal expansivity coefficient is nearer that of plain carbon steel.

The use of austenitic weld metal has been employed to join hard steels, such as wear-resisting members, armor plate and cast irons sensitive to thermal stresses. Occasionally it is employed as an intermediate weld metal placed on the sides of the weld groove with a harder or stronger filler metal in the center. Obviously the 25–20 metal is used only as a ductile junction material and does not maintain a continuity of the properties of the base metal.

Most of the alloy steels applicable for weldments are neither fully ferritic, fully austenitic nor fully martensitic in their final condition. In order to obtain high strength without excessive brittleness it is necessary to obtain austenitic transformation products which are intermediate between martensite and the ductile but weaker structures of coarsely lamellar pearlite or the extreme soft spheroidized ferrite-cementite aggregates. This may

be accomplished by using medium or low alloy steels with a suitable heat treatment to permit the transformation to proceed to the necessary extent. An alternative is to substitute strengthening alloy elements for the carbon. By the proper balancing of several elements of dissimilar characteristics the strengthening may be obtained without great loss of ductility that accompanies strictly additive contributions.

Austenitic Transformation Effects of Alloy Elements in Steel

Properly selected additions of nearly all alloying elements increase the strength of iron and steel to some degree. The influence of each element may not always show a consistent trend with each addition and may be modified by associate elements in the steel. Furthermore, the effect of alloy elements in the base materials of weldments is quite dissimilar from that in the weld metal. Although the reasons for this difference are not well understood, it is appreciated that the segregation patterns of weld and wrought or cast metals are entirely dissimilar. Moreover, weld metal is highly superheated and probably supercooled.

The possible contribution of alloy elements to the strength properties of steel depends on the phase structures that they promote or modify. A list of the phase modifications would include the following:

1. Stabilization of ferrite.
2. Stabilization of austenite.
3. Formation of free (non-pearlitic) carbides in various orders of aggregation, distribution and coalescence.
4. Retardation of the austenitic transformation to the extent that martensitic or hard nodular structures are obtained unless inordinately slow cooling rates to room temperatures are employed.
5. Acceleration of the austenite transformation so that lamellar pearlite or other ductile aggregates of ferrite and cementite are obtained at normal rates of cooling to room temperature.
6. Solid solution in ferrite.
7. Solid solution in austenite.
8. Grain refinement by extensive and nearly simultaneous recrystallization or by inhibition of grain growth.
9. Precipitation of finely divided bodies in a highly dispersed distribution in solid solution matrix (aging).

Consideration has already been given to the first three structures such as the stable phases of ferritic and austenitic steels and to carbides which are only difficultly soluble in austenite at elevated temperatures. Carbides such as those of tungsten, molybdenum, chromium and manganese are much harder than cementite and are employed as major constituents of hard surfacing alloys applied by welding. Many of these are complex compounds sharing the carbide with iron or other carbide-forming elements. Most of the carbides of significance in weldable steels are the products of the austenite transformation and will be considered in this connection (see Fig. 11).

In order to have a reasonably accurate measure of the effect of alloy elements in the austenite transformation, it is advantageous to compare the time periods required for complete isothermal transformation of alloy steels at different temperatures. This information is pertinent to the weldability

of the alloyed steel and to the extent of preheat or post heat that is required to give satisfactory physical properties. Where the delayed cooling cannot be controlled to the necessary nicety, a subcritical heat treatment to follow these techniques may be required. Although base and weld metals of the same nominal composition respond differently to heat treatment, the same metallurgical principles apply to both.

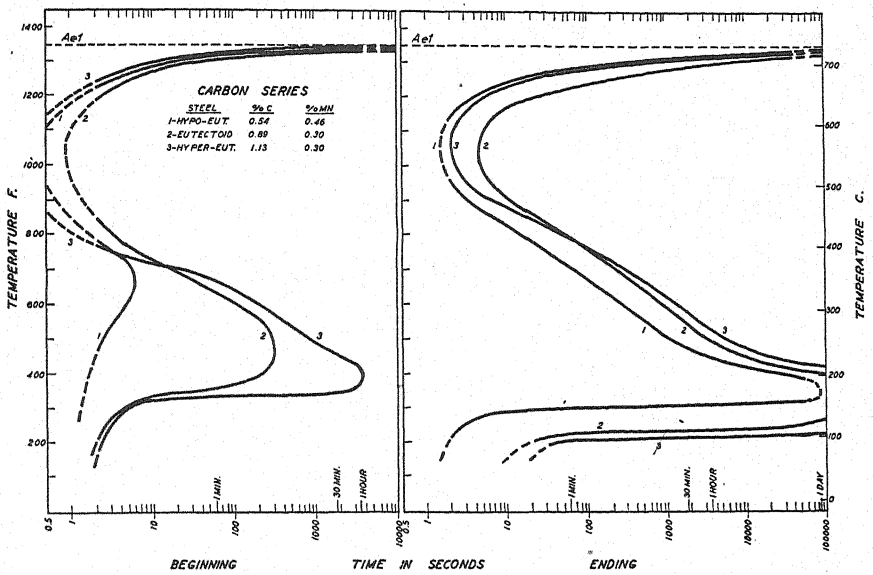


Fig. 11—Comparison Chart Showing the Influence of Carbon on the Isothermal Transformation Curve

(S curves in this Chapter furnished through the courtesy of the U. S. Steel Corp.)

Molybdenum is one of the most effective elements which delay the isothermal or constant temperature austenitic transformation. The transformation diagram as reported by Davenport is shown in Fig. 12. It should be compared with that of plain carbon steel as a standard. Near 1000°F. (538°C.) a peculiar effect to the upper part of the completion curve is imparted by this element. The character of the lower parts of the curve is less definitely known. In contents up to 0.5% molybdenum causes much more sluggishness than chromium, but between 0.5% and 0.8% the additional effect is not great.

Chromium is similar to molybdenum in its general influence on the S-curve, but it acts to a less marked degree. Figure 13 shows these effects. The higher the chromium content, the more pronounced is the characteristic modification of this so-called S-curve. The nose temperature near 900°F. is also raised accordingly with an elevation of the critical temperature. In some chromium-bearing steels a transformation or austenitic decomposition in two stages below 900°F. (482°C.) has been observed.

Figure 14 shows that manganese retards the isothermal transformation at all temperatures, but on increasing content, the S-curves retain the

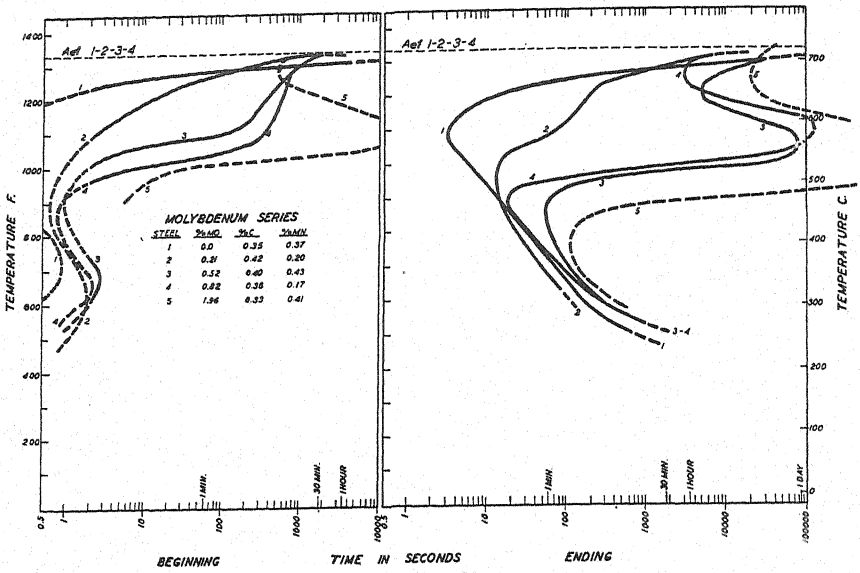


Fig. 12—Comparison Chart Showing the Influence of Molybdenum on the Isothermal Transformation Curve

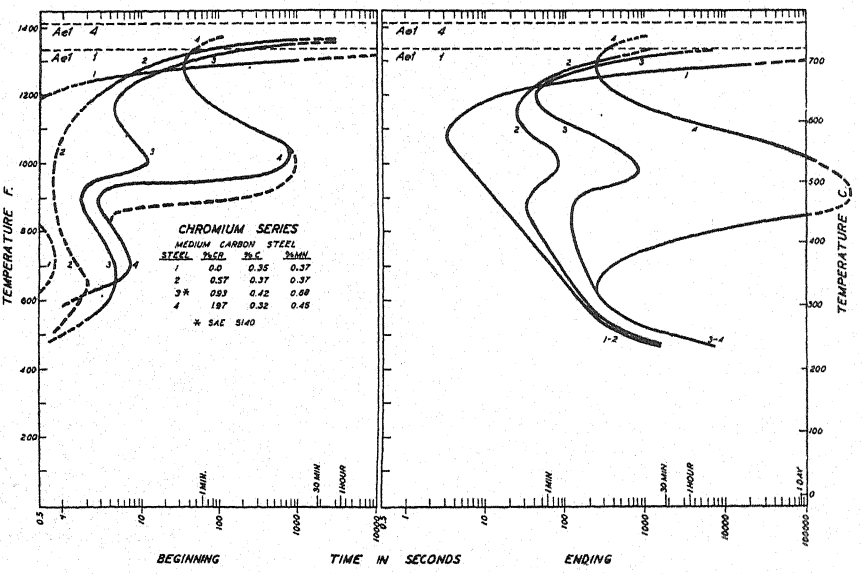


Fig. 13—Comparison Chart Showing the Influence of Chromium on the Isothermal Transformation Curve

same symmetry. Manganese is not as effective as chromium in its retardation.

Nickel consistently delays the austenitic transformation at all temperature levels, but is less effective than manganese. It lowers the critical temperature on cooling. Isothermal transformation curves are shown in Fig. 15.

Vanadium appears to ordinarily retard the transformation below the nose temperature of the S-curve but to accelerate it at higher levels.

Cobalt is unique in that it is the only alloying element which has been observed to increase the rate of the austenite transformation.

The S-curves have only been studied for base metal steels of moderate alloy content and with higher carbon contents than are employed in most steels which are welded. At higher alloy or lower carbon contents the ferritic tendencies of some elements might change these trends. Further alloying can modify the effect of associate elements, as exemplified by the effect of 0.20% aluminum to increase the transformation rate in 12% chromium steel. Strong carbide-forming elements can decrease the carbon solubility in austenite and consequently its hardening tendency.

The maximum cooling rate in degrees per minute which permits transformation to non-martensitic products can be derived from the isothermal curves using the same expression applied to plain carbon steels. The maximum rate for coarse grain steel is given by:

$$r = \frac{T_0 - (T_1 - 100)}{1.5t_2}$$

For fine grain material the rate is half that of above. Consequently, the grain-refining elements, such as aluminum and vanadium, are not only effective by nucleating wide-spread recrystallization of a large number of fine grains on reheating, but also by aiding in rapid transformation on cooling.

By proper selection and judicious balancing of alloy elements, strong tensile and yield strength steels of relatively low alloy contents have been obtained which do not harden readily on cooling from the welding heat. A number of useful proprietary steels have been developed which in addition to good weldability may have special properties of moderate corrosion resistance, high yield to tensile strength ratio and not excessive cost in proportion to the strength improvement. The design of lightweight construction is made possible by these properties, together with the use of welding fabrication.

Alloy Elements in Solid Solution

Irrespective of their effect on the phase transformation and its products, nearly all alloy elements contribute to the strength of austenite or ferritic solid solutions. In some readily weldable steels this contribution to ferrite is utilized, since it can substitute for the effect of carbon and carbides. The hardness variations of ferrite show very little response to differences in the rate of cooling from high temperatures.

Among the usual accompanying elements in plain carbon steel, manganese up to some 0.80% and silicon up to 0.35% are considered essential to

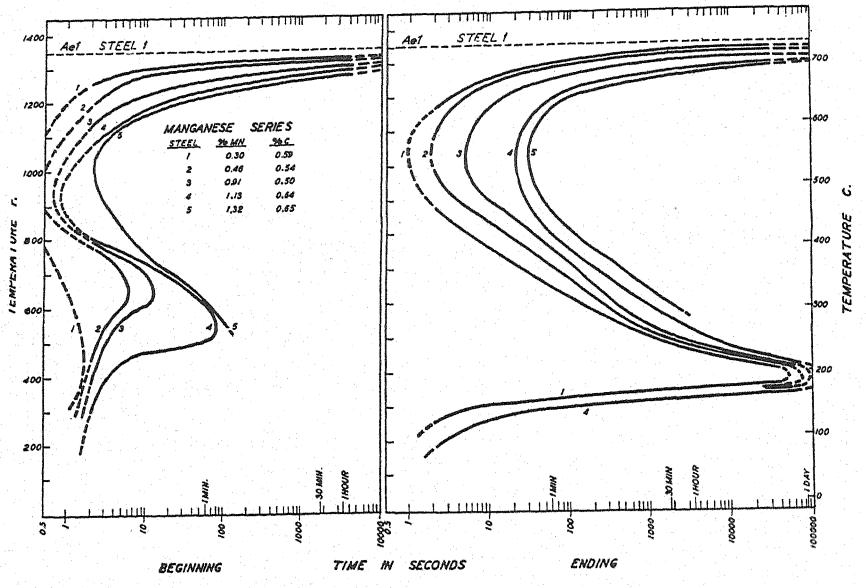


Fig. 14—Comparison Chart Showing the Influence of Manganese on the Isothermal Transformation Curve

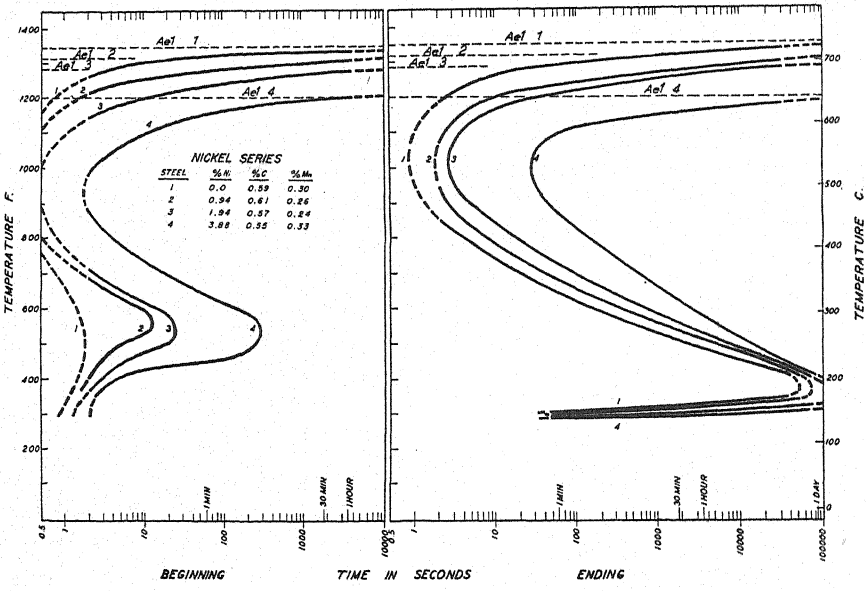


Fig. 15—Comparison Chart Showing the Influence of Nickel on the Isothermal Transformation Curve

good steel-making practice. However, they also increase the strength of ferrite and if much above these limits can be regarded in part as deliberate alloying additions. Phosphorus is usually limited to some 0.030 to 0.040%, but in some steels may be specifically added to some 0.10 to 0.15% content. Since its hardening and strengthening action is independent of cooling or quenching action, it replaces carbon for "fool-proof" welding steels. It also contributes to atmospheric corrosion resistance, usually with copper additions.

Residual alloy elements, such as small amounts of nickel, chromium and molybdenum, are sometimes incidentally included in steel. Up to some 0.25% they are slightly ferrite hardening.

Copper up to 0.50% strengthens ferrite by solid solution and since it is not easily lost by oxidation is accumulative on remelting of scrap.

Other metallic elements are rarely present except by deliberate addition, since they are less rarely found in the melting stock. Many are eliminated by oxidation during the steel-making process.

Precipitation hardening from ferrite solid solution, especially from weld metal, can be expected in the case of some oxides, nitrides and carbides, as well as copper. After rapid cooling the precipitation proceeds slowly at room temperatures, which is called "aging." The distribution is highly dispersed and correspondingly effective as a strengthening process. Copper in excess of 0.5% will show precipitation hardening in steel.

Conclusion

The principles of ferrous metallurgy are utilized in welding practices even when the direct relationship may not be apparent to the operator. Translation of these fundamentals into individual practices requires a detailed consideration, which cannot be given in this chapter. However, specific procedures are considered elsewhere in this HANDBOOK.

For continued advance in welding technology, the metallurgy will require considerably more research than has hitherto been afforded it. The nature of weld metal deposits is quite dissimilar from that with any other industrial fusion process and its response to fabricating treatments is correspondingly different. It is generally recognized that most steels can be welded in a satisfactory manner and without embrittlement if proper precautions are observed. However, to establish exact conditions for welding the more difficult steels with more exacting requirements is a purpose which lies ahead.

METALLURGY OF WELDS IN NICKEL AND HIGH-NICKEL ALLOYS

The metallurgy of welds in nickel and high-nickel alloys is, for the most part, quite uncomplicated. Unlike the steels, no high-temperature transformations are involved. The effect of the welding operation on the metal adjacent to the weld, outside of a moderate increase in grain size in a narrow zone, can be considered negligible. The absence of any phase changes makes preheating or post-heating unnecessary, the hardness and ductility of the heated zone being essentially independent of the cooling rate.

In addition to the main constituents of these materials, all contain small but important amounts of residual deoxidizer elements, originally added to the metal to produce a sound ingot possessing a satisfactory degree of hot and cold malleability. In making welds it is therefore, important to avoid puddling which would result in excessive volatilization or over-oxidation of the residual elements. In some instances, a filler wire is used which contains excess deoxidizers to compensate for losses in welding, and to impart soundness to the weld deposit. In arc welding, special core wires may be used for the same purpose and deoxidizers may, in some cases, be added through the electrode coating. The coating also functions to maintain a protective atmosphere about the arc, further assisting in the retention of residual deoxidizers.

In the gas welding of Inconel and other high-nickel-chromium alloys, it is important to use a neutral flame, as 0.15 to 0.40% of carbon can be introduced by the use of a moderately to strongly reducing flame. Such high-carbon welds sometimes are susceptible to corrosion, and carbon pickup should be avoided for that reason.

Lead, even in very small amounts, is a dangerous impurity in all nickel-base alloys, as it causes hot cracking. Contamination of the weld with sulphur may also produce hot cracking, and this element should likewise be essentially absent from the fusion zone.

Typical microstructures of arc welds in nickel, Monel and Inconel are included in Chapter 24 on Welding of Nickel and High-Nickel Alloys. The structures are similar to those of chill castings in these metals. The microstructures of oxyacetylene welds show considerably less pronounced coring and a somewhat larger grain size than corresponding arc welds, and may be considered in these respects somewhat analogous to sand castings.

COPPER AND COPPER ALLOYS

Foreword.—Tables showing the compositions of the various copper alloys discussed herein as well as information on the more practical aspects of their welding metallurgy will be found in Chapter 22. The more fundamental effects of the various elements upon the copper alloys and reactions occurring in welding operations will be discussed in this Chapter. Only those reactions and properties of interest to the welding metallurgist are given.

Elements and Oxides Involved.—Fifteen elements listed in Table 3 are involved, one or more at a time, with copper in the various major commercial copper alloys. Many others, eighteen of which are briefly discussed below are occasionally used with copper to form alloys but they are employed in such small amounts or for such highly specialized purposes as to be but rarely encountered in welding operations.

Minor Additions to Copper and Copper Alloys

In this group we mention eighteen elements, as follows: (1) Barium, (2) Boron, (3) Calcium, (4) Lithium, (5) Magnesium, (6) Sodium, (7) Titanium, (8) Vanadium, (9) Antimony, (10) Tungsten, (11) Selenium and (12) Tellurium.

NOTE: Of these twelve elements, the first eight may be used as deoxidizers for copper though phosphorus, silicon, zinc, manganese, chromium, cadmium, aluminum or beryllium are usually preferred for this purpose. Magnesium is also used as a desulphurizer in the nickel alloys but manganese is usually preferred for this purpose.

Antimony is used in a few hundredths per cent to raise the annealing temperature of copper above the temperature of soft soldering operations. Silver is also used to this end. A compressed and sintered mixture of tungsten and copper powders makes a hard, heat-resisting material of good electrical conductivity for spot-welding electrodes. Selenium or tellurium may be used in cold drawn, high-conductivity copper to promote free machinability.

(13) Bismuth is very objectionable in copper as a few thousandths of 1% makes the metal hot short and prone to crack in forging or welding operations.

(14) Sulphur is particularly objectionable in the cupro-nickel alloys in which 0.005% of sulphur will allow the formation of sufficient of the low-melting (1190°F.) eutectic of Ni_3S_2 + Ni as to make the metal hot short and likely to crack in welding if there is insufficient manganese, magnesium, zinc or aluminum to ameliorate its harmful effect.

(15) Carbon is practically insoluble in copper. It is more soluble in a copper-nickel alloy, but it is rigidly excluded in commercial practice as it has a tendency to precipitate along the grain boundaries as graphite, making the metal brittle. (16) Cobalt has been used with copper in some highly specialized alloys for spot-welding electrodes but its use is strictly limited. (17) Gold alloyed with copper in coins and jewelry is gas welded without difficulty.

(18) Mercury has a tendency to penetrate into a copper alloy along the grain boundaries when it is under a tensile stress thus promoting cracking. Mercury should be kept strictly away from contact with the copper alloys.

In addition to the eighteen elements which are involved in some minor or unusual way in copper-alloy metallurgy, Table 3 lists fifteen elements which play a major part in commercial copper and copper alloys. Finally, consideration must be given to the effect of elementary and combined gases as oxygen, hydrogen, water vapor, carbon monoxide, carbon dioxide and nitrogen.

In particular oxygen must be given special consideration. Since oxides are almost invariably formed in the welding of copper alloys, it is quite necessary that the welding metallurgist know something of their properties. For this reason they are listed in Table 3. Where there are two or more oxides formed, the two are given which are formed (*a*) when there is a preponderance of the metal element and (*b*) when there is a preponderance of oxygen.

Effect of Heat Alone on the Copper-Alloy Base Metal.—The cold work strength obtainable in a copper alloy may be, in the case of some spring wire as much as 350% of the annealed strength but usually for copper and brass it varies from a 10% to a 100% improvement depending upon the degree of strength, hardness and residual ductility desired.

An application of heat of sufficient intensity and for a sufficient time to a copper alloy which has been thus cold work-hardened, will first cause relief of its residual stress and then recrystallize and soften the metal. The temperature at which this softening or annealing begins depends upon

Table 3—Elements Used with Copper, Oxides, etc.

Element	Melts, °F.	Boils, °F.	Oxides			
			Formulas	Melts, °F.	Boils, °F.	Nature of Oxide on Weld Pool
Aluminum	1218 (659)	3272 (1800)	Al_2O_3	3722 (2050)	4082 (2250)	Tough, refractory. Floats but is apt to be folded in
Arsenic	1139 (615)	Subl.	As_2O_3	379 (Subl.)		No interference
Beryllium	2345 (1285)	5040 (2782)	BeO	4658 (2570)	7100 ± (3900 ±)	Tough, refractory. Floats but is apt to be folded in
Cadmium	610 (321)	1413 (767)	Cd_2O CdO	1652 (d.) (900)		No serious interference but high density, 8.2, may cause the suboxide to be entrapped in the metal
Chromium	3350 (1843)	4500 (2482)	Cr_2O_3 CrO	3614 (1990)	Very high	Refractory, brittle,
Copper	1981 (1083)	4200 (2315)	Cu_2O	2255 (1235)	3272 (a)	Easily reduced, easily fluxed, CuO dissolved in melt
			CuO	1879 (d.) (1026) (d.)		
Iron	2795 (1535)	5430 (3000)	FeO	2588 (1420)		Easily fluxed, easily reduced with carbon monoxide. Not important in copper alloys
			Fe_2O_3	2849 (1565)		
Lead	621 (327)	3170 (1743)	Pb_2O	(d.)		Unstable. Causes porosity. Heavy, sinks in melt. Fluxible
			PbO_2	554 (d.)		
Manganese	2268 (1242)	3905 (2152)	MnO	3002 (1650)		Readily fluxed. High oxide unstable
			MnO_2	995 (a) (535)		
Nickel	2646 (1452)	5252 (2900)	NiO to Ni_2O_3 Ni_3O_4	752 (400)	1112 (a)	Tight, closely clinging, refractory scale

Phosphorus	(Ig.) 93		P_4O_6	72 (22.5)	343 (173)	Acts as deoxidizer, fluxlike
			P_2O_5	1045 (563)	657 (347) (Subl.)	
Silicon	2588 (1420)	4712 (2600)	SiO_2	3115 (1713)	4046+ (2230)	Element is a strong deoxidizer. Oxide combines with other metal oxides to form glass melting at 1600°F. ± to form continuous, impervious, flux-like film on the weld pool
Silver	1761 (961)	3635 (2002)	AgO	572 (d.) (300)		Sublimates. No interference
Tin	450 (232)	4118 (2270)	SnO	1292 (d.) (700)	1742 (950)	Easily fluxed, easily reduced with phosphorus
			SnO_2	2060 (d.) (1127)		
Zinc	786 (419)	1665 (907)	ZnO	3272 (Subl.) (1800)	3272 (1800)	Zinc vaporizes before oxide is formed. Easily fluxed

NOTE: Degrees centigrade given in parentheses. (d.) = decomposed. (Subl.) = sublimates. (a) = loses oxygen at temperature indicated. (Ig.) = ignites.

the composition and upon the amount of previous cold work. In general it is lowest for pure copper, a temperature of 374°F. (190°C.) for a short time causing some softening. Hence, cold-rolled pure copper can be softened appreciably by the moderate temperatures, 420 to 470°F., used in soft soldering operations. The higher temperatures of brazing and welding will of course anneal it completely.

Copper for fabrication into sheet, tubes and wires, which are cold work-strengthened, is often improved in its annealing temperature by small additions of other elements. Thus the additions of elements used singly will raise the softening point of cold-worked copper to approximately the following temperatures:

Element	Per cent Added to Copper	Approximate Softening Temperature of Work Hardened Copper, °F.	
Silver	0.10	617	(325°C.)
Arsenic	0.14	482	(250°C.)
Phosphorus	0.10	617	(325°C.)
Antimony	0.10	707	(375°C.)

Thus the alloying of the copper with only a few hundredths per cent of one of these elements will make it quite resistant to any heat effect (softening) in soft-soldering operations. Cold-drawn copper tubing, for example, which carries 0.01 to 0.03% phosphorus can be safely soft soldered with little if any annealing effect.

Where the copper is alloyed with appreciable amounts of other elements as is the case with brass, bronze, nickel silvers, cupro-nickels, aluminum bronze, copper cadmium alloys, etc., the softening effect of heat rarely begins at temperatures below 500°F. (260°C.) and even at temperatures as high as 1200°F. (650°C.) an appreciable length of time for complete annealing is required. Hence most of these cold-worked commercial copper alloys may, as far as softening effect is concerned, be soft soldered with no loss of strength. Also, since the heating period for most silver-brazing operations is so short, they may be silver brazed at 1200°F. and still retain a considerable proportion of their cold work strength.

Brazing operations at 1650°F. and fusion-welding operations at still higher temperatures will usually result in dead soft metal at the braze or weld. However, resistance spot and seam fusion welds in cold-rolled sheet are made in such brief intervals and the fusion temperature is so sharply localized that a considerable proportion of the cold work strength may be retained in the finished connection.

Oxides on Solid Surfaces.—Another effect of the initial heating of the base metal preparatory to soldering, brazing or welding operations is to cause a thin layer of metal oxide to form on exposed surfaces. With some alloys which develop an oxide which is not easily fluxed, this oxide may interfere seriously with subsequent soldering, brazing or welding operations. Thus copper alloys containing beryllium, aluminum and to a lesser extent, silicon, chromium or nickel develop oxides on the hot, solid metal which interfere with subsequent soldering and brazing operations.

The best way to avoid difficulties from this source is to start with a

chemically or mechanically cleaned surface and cover with a suitable flux *before* the heat is applied. The ability of any thin layer of flux to dissolve metal oxides is strictly limited.

The flux used in this manner should melt as early in the heat application as possible and continue as a stable liquid until the final temperature of the operation is reached. In order to fulfill this condition, the flux is often made up of two or more constituents one of which melts at a low temperature and the other near the final temperature of the operation.

Some of the constituents which have a high affinity for oxygen such as beryllium and aluminum may develop an oxide coat on the metal in the absence of atmospheric oxygen. Thus they may take oxygen from water vapor, carbon dioxide or even from sodium tetraborate (borax). These gases and fluxes cannot, therefore be regarded as being protective or neutral on aluminum bronze, beryllium copper or chrome copper though they may actually be neutral and protective to copper, brass and the usual bronzes.

Gassing of Oxygen-Bearing Copper.—A reaction that takes place in hot, solid, tough pitch copper in an atmosphere containing hydrogen is the reduction of the particles of cuprous oxide in the metal by such hydrogen that has diffused into it, thus

$$Cu_2O + H_2 = Cu_2 + H_2O$$

This reaction begins with a temperature of 750°F. (400°C.) in the copper and increases with the temperature. This reaction is not observed in an oxygen-free or a deoxidized copper or other copper alloy. It may cause a loss of strength of as much as 50% in a weld in oxygen-bearing copper.

The action of fusion welding heat alone on copper containing cuprous oxide will cause some rejection of the latter to the grain boundaries with some weakening effect. Thus in carbon arc welding of tough pitch copper an efficiency of only 70 to 90% may be expected in the weld even if there is no hydrogen present in the arc. The use of a deoxidized copper base metal avoids weaknesses resulting from the presence of cuprous oxide in the metal.

Surface Alloying Effects.—In common with most other metals, copper alloys will develop a bond rapidly with soft solders, silver solders and brazing alloys. Not much information has been published on the exact mechanism of this bond.

Aside from the effects described above, the only other result of welding or brazing operations on copper and copper alloys in the solid base metal adjacent to the weld is a slight enlargement of the grain. Since this grain size rarely becomes as great as that of the weld metal, it may usually be disregarded. No harmful chemical or solution changes take place in the heat-affected zone except in the case of beryllium copper, nickel copper, or chrome copper in which there may be an undesirable softening of the heat-treated alloy.

Thermal Conductivity of Copper.—The high thermal conductivity of copper, commercial bronze and red brass should be mentioned as it is the property which gives the most trouble in welding operations. Thus in raising the temperature of the edge of a copper sheet to the fusion point,

difficulty is experienced owing to the rapid transfer of the heat to the more remote parts of the metal.

It is often necessary, therefore, to preheat before the welding temperature can be attained in the desired location. The temperature of the preheat may be from 600 to 1000°F. in the area near the weld before the actual welding torch or arc can go into action with a reasonable speed.

Reactions in the Molten State

Copper when molten, oxidizes readily and some of the oxide is dissolved in the melt as cuprous oxide unless there is a deoxidizer present to reduce it as fast as it forms. Phosphorus, silicon, manganese, zinc, aluminum, beryllium as well as several minor elements will do this. Phosphorus is used for this purpose more than any other element, the 0.02 to 0.03% of phosphorus remaining in the metal being sufficient to keep oxygen out of the fused base metal. The filler rod should also carry a suitable deoxidizer, silicon and/or manganese being preferred to phosphorus and used in amounts from 0.05 to 0.25%.

The copper oxides are readily reduced by the hydrogen and carbon monoxide gases in the oxyacetylene flame and as readily dissolved in the borax base fluxes.

The phosphorus in the molten base metal evaporates gently from the weld pool reducing any oxide that may have formed on the surface and the resulting phosphorus pentoxide itself disappears as a vapor leaving the melt with a mirror clear surface. The phosphorus will reduce the manganese oxide as well as that of copper but not that of silicon. Silicon, if present in the filler rod, oxidizes the instant a drop is melted from the rod and combines with other metal oxides to form a glass which is a liquid at the melting temperature of copper. This silica glass film is continuous over the molten metal and impervious to the atmosphere and the torch gases. Silicon is therefore a distinct aid in promoting soundness.

The tough pitch and deoxidized copper are very nearly pure elementary metals. Hence, they pass from the completely solid state with but a slight change in temperature, to the completely liquid free-flowing state.

Major Alloying Elements

General.—Besides the three elements mentioned above (phosphorus, silicon and manganese) which are added to copper in small fractions of a per cent, the elements of Table 3 are alloyed with copper, one or more at a time, to make the commercial copper group metals. These elements are taken up one at a time and their metallurgical reactions, as they occur in copper during soldering, brazing and welding operations discussed.

A primary effect resulting from the addition of other elements to copper is a sharp reduction in the electrical and thermal conductivities. Generally speaking, the thermal conductivity of copper alloys, excepting deoxidized copper and copper-zinc brasses containing less than 15% of zinc, is sufficiently depressed so that it is not the obstacle to welding operations in most copper alloys that it may be in the case of pure copper.

Aluminum.—Aluminum bronzes with aluminum up to 10% in wrought metal, and up to 14.5% in cast metal, the remainder being copper alone or

copper with minor additions of iron, nickel, tin or manganese, are characterized in the hot solid state by good forgeability and non-scaling qualities.

The scale-resisting property is due to a thin, continuous coating of the refractory aluminum trioxide which is also responsible for the difficulty encountered in gas welding the aluminum bronzes unless suitable fluxes are used.

Ordinary blanketing action of the metal with the oxyacetylene gases and usual fluxes is futile as the aluminum will reduce water vapor or take oxygen from the borax flux. The aluminum oxide keeps the torch and the atmosphere gases from contact with the molten metal so that good soundness is obtained.

In carbon arc welding, the metal is melted rapidly and a very satisfactory weld can be made. Covered metal-arc electrodes give even better protection to the metal. When the metal is run in more than one pass, the oxide should be ground from the surface before a second deposit is made.

Arsenic.—Arsenic causes no interfering or beneficial metallurgical reactions in welding operations.

Beryllium.—Alloyed with copper to the extent of $2^1/_2\%$ or less, beryllium forms a high strength, heat-treatable alloy which is difficult to gas weld because of the formation of the refractory, continuous, unfluxible oxide on the molten metal. It becomes folded into new deposits preventing a satisfactory confluence of the newly fused metal with that previously melted. The more rapid action of the carbon arc enables one to make a satisfactory fusion weld or to flow beryllium copper on solid copper or steel. Such fusion welds will be soft and a full heat treatment is necessary to obtain full strength. In deposits of two or more passes, the oxide of the first pass should be ground off before another deposit is made.

Cadmium.—This element in copper to the extent of $1^1/_4\%$ offers no serious difficulty in fusion welding operations. It evaporates rather easily at the fusion welding temperature of its copper alloy. A small amount of the heavy oxide may be entrapped in the molten metal but as it is fluxed without difficulty, this is not serious. It is welded by gas and the carbon arc. In arc welding, however, good ventilation should be provided in order to avoid harmful toxic effects of cadmium vapor.

Chromium.—Like aluminum and beryllium, chromium forms on the weld pool of the copper chromium alloy (which rarely carries more than 1% of chromium) a refractory oxide which makes gas welding difficult except with special fluxes. Carbon arc welding is possible but the weld requires a full heat treatment to enable the maximum hardness, strength and conductivity to be obtained.

Iron.—Used in very limited proportions of 0.5 to 1% in manganese bronze and somewhat higher proportions in aluminum bronze, iron interposes no difficulty in gas or arc welding.

Lead.—Pure lead can be gas welded without difficulty though the weight and fluidity of the molten metal makes vertical or overhead welding difficult. In the copper alloys, it gives trouble in neutral flame gas fusion welding by reason of hot shortness and high specific gravity and instability of the oxide. The heavy PbO_2 sinks in the melt, gives up oxygen to become

Pb_2O which, with a slight variation in conditions is decomposed. The best procedure is to use an oxidizing flame which helps to stabilize the higher oxide and plenty of flux which will dissolve a reasonable amount of the lead oxide. The leaded copper alloys are rarely arc welded.

Manganese.—This element occurring in the usual commercial copper alloys such as manganese bronze, deoxidized copper and silicon copper alloys in proportions of 0.05 to $1^1/_4\%$ offers no difficulty in gas- or arc-welding operations. The high oxide is unstable but the low one is not and it is readily fluxed. In copper alloys containing no silicon, manganese is evidenced in gas welding by the presence of high-velocity, dull red sparks from the melting metal. In any alloy containing both manganese and silicon, no sparks are thrown off but the manganese oxide combines with the silicon and copper oxides to form a low-melting, flux-like glass.

Nickel.—The nickel oxide does not form on the hot solid metal at as low a temperature as do the oxides of aluminum, beryllium, chromium or silicon. The copper nickel alloys are, therefore, easier to soft solder than alloys containing copper. In brazing and silver soldering operations the nickel oxide offers no appreciable interference.

In gas fusion welding, however, the nickel oxide may interfere with the flowing of the metal. It is a closely clinging, refractory film which causes the metal to solidify with a rough, cinder-like surface. Difficulties from this source can be avoided by the initial application of a heavy paste of boron suboxide or other suitable flux.

In all of the copper-nickel alloys, it is important that there be sufficient deoxidizer or desulphurizer so that there will be a residual amount of a few hundredths per cent in the solidified weld metal. Manganese is the element most often used for this purpose. In the nickel silvers, the zinc serves to this end as well as being a major alloying constituent.

Difficulty from the nickel oxide is also avoided by the use of flux-coated metal-arc electrodes.

Phosphorus.—When used in larger amounts than 0.25%, as for example 4 to 8%, phosphorus acts much the same as when used in smaller amounts, i.e., the phosphorus will evaporate slowly from the melt keeping the oxide from forming on the surface and resulting in a bright weld pool.

The presence of this amount of phosphorus makes the molten phosphorus-copper alloy exert self-fluxing properties on copper and brass. The phosphorus from the solder reduces the copper oxide on the base metal and flows into place.

Where the phosphorus-copper alloy is used as a solder, cracking of the solder does not take place as it is deposited on a solid base metal usually cool enough to cause quick solidification of the solder.

Silicon.—Silicon is used both as a deoxidizer and as a major alloying element to improve strength, workability and ductility. The alloy containing it cannot be melted either with gas or the arc without the formation of a continuous film of liquid glass on the weld pool. The silicon oxide forms on the solid metal at temperatures as low as 400°F. interfering with soft soldering operations unless a flux is applied before the metal is heated. On the molten metal this film is flux-like in nature and protects it from further oxidation and contamination from the welding gases.

It does not, however, insure complete soundness of the metal. Some gas may be in the metal from the original casting and where the fusion takes place with extreme rapidity as under a carbon arc, some gas may get into the metal before the film is completely formed.

Water vapor is particularly bad in this respect. If it is permitted to come up through the weld metal when the latter is being quickly fused by the arc and quickly solidified, a bad bright-surfaced gas porosity develops in the weld metal. This is attributed to the reaction $2H_2O + Si = SiO_2 + 4H$. In oxyacetylene welding, the much longer heating-up period allows the water to evaporate from the plates and flux before actual fusion begins and the water vapor in the torch flame cannot get into the metal through the impervious liquid silica glass film. Gas welds are, therefore, quite free from this type of porosity.

The copper silicon alloys have good ductility cold and also at elevated temperatures having exceptionally good forgeability in the range between 1200° and 1600°F. Near the melting point, the metal is hot short and care must be exercised in bending or stressing the metal until its temperature has dropped below 1700°F. In the case of arc welding, the time in passing through this hot short temperature range is very brief so that no trouble is experienced from contraction during this critical range except in laying on the initial bead in very heavy and rigid plates.

Silver.—This element is a beneficial agent in most copper alloys but owing to its cost is not commonly used as a major alloying constituent except in the silver solder group As a minor constituent in proportions up to 0.04%, it is responsible for a decided improvement in the annealing temperature of copper. Used in larger amounts, the annealing temperature does not improve in a direct ratio to the addition. In amounts of approximately 1% it is used in copper filler rods with a very slight advantage in causing a lowered melting point and smaller grain size. It does not improve the strength, soundness or ductility.

Tin is one of the three most important major alloying elements used with copper. It is used in amounts up to 11% in wrought alloys and in larger amounts up to 30% in cast alloys. Tin has a decidedly hardening and strengthening effect on copper.

In welding operations where the tin is not protected by a deoxidizer such as phosphorus or zinc, the tin oxidizes preferentially to the copper and the tin oxide is prone to be caught in the weld metal making the latter weak. The tin oxide is, however, easily fluxed. It does not form a complete crust over the weld pool as do some of the elements mentioned above. The element has a high boiling point so that no metal is lost by evaporation even when superheated with the blowpipe or arc.

Zinc is commercially the most important alloying element used with copper. It is used in cold- and hot-worked brasses up to 41% and in brazing solders up to 50%. A characteristic of all of these copper zinc alloys is the relative ease with which zinc is evaporated from the melt with but very slight superheat.

Because of the difficulty in avoiding superheat when brass is melted with the arc either as a base metal or as a metal arc electrode, there is invariably a serious loss of zinc in welding with the arc. The arc is not, therefore, recommended for welding brass though in some cases the carbon arc

is used with a zinc-free welding rod such as phosphor bronze or a copper silicon rod. The oxyacetylene flame being used with closer control of the weld metal is preferred.

The zinc oxide is easily fluxed. Very little of it appears on the weld pool unless a strongly oxidizing flame is used in which case a film forms which suppresses in a large measure the further evaporation until the metal is given an appreciable superheat. A film of silica glass is also useful in this respect, a fractional per cent of silicon being a constituent of many of the zinc bronze welding rods.

These welding rods all have sufficient zinc, 38 to 41%, to develop in the weld metal a considerable proportion of the hard, strong beta brass constituent. Fortunately this beta constituent is soft and ductile in the temperature range between its melting point and about 875°F. Hence, there is no danger of hot short cracks forming in such weld metal and residual stresses do not build up to serious proportions even when such weld metal is used in very rigid welds in heavy cast iron and steel sections.

Zinc does not cause as abrupt a reduction in electrical and thermal conductivity in copper as do many of the other elements. The brasses, therefore, require considerable heat when being welded, especially with zinc contents of 5 to 15%—the gilding metals, commercial bronzes and red brasses.

Brasses having 25% or less of zinc can be brazed with the high zinc bronzes and spelter solders without fusion of the base metals. The common brasses, naval brass and manganese bronze must be fused with the high zinc bronze filler rod to secure the most satisfactory connection.

Effect of Gases

The effect of hydrogen on solid copper-bearing cuprous oxide has been described above. Some hydrogen will be rejected as the metal solidifies and, if the solidification is too fast, be entrapped in the metal causing bright surfaced spheroids and worm holes.

Nitrogen and carbon dioxide are thought to be nearly insoluble in the molten copper alloys, while carbon monoxide is thought to be only slightly soluble in the molten copper alloys.

After Treatment

In none of the copper alloys is there a hard, brittle constituent developed comparable to the martensite in chilled steel. No matter how quickly the weld metal is solidified and cooled, it is always soft and the yield strength relatively low. Hence, a relief anneal is not as necessary in the copper alloys as it is in the ferrous metals.

However, the weld metal in a copper alloy weld in common with other metals partakes of the nature of soft cast metal with large grains and a columnar structure. It may be desirable, therefore, to give the weld metal a suitable aftertreatment when a fine grain with the maximum in strength and ductility of the finished weld is required.

The aftertreatment which is most effective is a severe peening of the cold weld metal followed by a short-time anneal at 1200°F. A slow passage of the

oxyacetylene flame along the peened weld, bringing the metal to a very dull red estimated at 1100 to 1200°F., is sufficient to recrystallize the metal without fully softening it.

Hot forging of the weld in copper will improve its quality but it is not often applied in this country.

Stress relief heat treatment is not often resorted to. The principal copper alloys used in welding operations have relatively low yield strengths at elevated temperatures so that stresses due to contraction cannot build up to high values. Usually a light peening will reduce the residual stresses to an unimportant value.

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CHAPTER 3

WELDABILITY OF STEELS*

Effects of Metallic Elements on the Making of Welds, Weldability of Plain Carbon and Low Alloy Steels, Effect of Carbon and Manganese, Tests to Determine Properties of a Welded Joint or Weldability of the Base Metal, Specification for Weldability, Tests Based on Ductility Measurements.

THE term "Weldability" does not have a universally accepted meaning, and many definitions have been proposed. A consideration of the many definitions indicates that this term relates primarily to the effect of the heat cycle imposed by the welding operation and manifested by hardening and a loss of ductility or cracking in relatively narrow zones adjacent to the weld. If the loss of ductility is small, the steel may be said to have good weldability. While hardening with attending loss of ductility is the main consideration, there are other factors that have a bearing on the weldability rating of a steel and are conducive to weld defects and failures. Porosity of the weld is also included and it may be said that a metal that produces excessive porosity is given a low rating. From the standpoint of actually making the welds, it can be fairly said that almost any homogeneous structural steel that can be made can be welded provided the welding engineer is allowed to specify his own conditions.

Welding involves the localized heating or melting of the metals to be joined, and the base metal is necessarily subjected to a steep temperature gradient in a relatively small mass of metal. The thermal effects are such that the composition and characteristics of the base metal are of extreme importance in considering the weldability of the steel.

In considering weldability from the practical standpoint, three things must be taken into consideration: (1) that the results that would be acceptable for one application may be entirely unacceptable for another; (2) the design and location of welding may be such that the results would be unacceptable and the metal or application considered unacceptable; (3) metal that is not weldable with one technique may be weldable by

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another. Removal of the restrictions by proper design for welding may render the metal weldable where otherwise it would not be so considered.

The selection of any metal for welding is dependent primarily on its properties and application, and what stresses it must endure, either static or dynamic. Chemical composition primarily and heat treatment secondarily will decide what metal to choose for the physical requirements.

Base metal factors that may affect the properties of a welded joint may be divided into (*a*) chemical, and (*b*) physical. The chemical factors are the usual elements found in plain carbon steels and the various alloys or metals added to impart special physical properties to the steel. They are:

(*a*) *Chemical:*

Carbon	Nickel	Tungsten
Manganese	Copper	Aluminum
Phosphorus	Molybdenum	Titanium
Sulphur	Chromium	Columbium
Silicon	Vanadium	

Solid solution strength and hardening of the heat-affected zone are the primary effects but a principal effect is an action on the carbide constituent and on grain size. Some are more effective than others in promoting high elastic ratio, e.g., copper, phosphorus and silicon. The presence of the various elements in single or multiple combinations in steels renders the steels more or less sensitive to the steep thermal gradients across a welded joint, with the result that some of them make steels of a given strength less weldable than others.

(*b*) *Physical factors:*

Surface condition—oxide, zinc, Al, etc.
Hardenability.
High temperature strength and ductility.
Homogeneity—distribution of non-metallic inclusions.
Grain size.

All of the chemical factors in the amounts usually occurring in commercial steels have little effect on the production of sound welds, with the exception of sulphur when segregated or high, which will be described later under a separate section.

While heat effect on the base metal is the main consideration in a study of weldability, there are instances where adverse effects may be attributed to the presence of non-metallic elements such as nitrogen, hydrogen, sulphur, phosphorus, oxygen, etc. The effect of these elements on weldability may be briefly considered.

Nitrogen.—Nitrogen in plain carbon and low alloy steels is considered as an impurity, and little information is available as to the effect of nitrogen in base metal on its welding qualities. The chief detrimental effect of nitrogen in steel is age hardening with its accompanying embrittlement. Open-hearth steels may contain 0.0015 to 0.008%, while Bessemer steels may contain as high as 0.030%, and in these quantities nitrogen exhibits no deleterious effects on the weldability. It may be said that even steels with higher amounts of nitrogen are readily weldable if other conditions are

correct. Generally speaking, nitrogen may be eliminated as a factor affecting the weldability of plain carbon or low alloy steels.

Nitrogen does play an important part in welding the high chromium alloys, particularly the low carbon-chromium irons. The addition of nitrogen to low carbon, high chromium irons (15–18% chromium and 23–28% chromium) acts to limit grain size in either cast or rolled products and to improve the strength and toughness without undue decrease in ductility. It also adds to the hot workability of the alloys. The presence of nitrogen has no adverse effect on the actual making of the welds. On the contrary, nitrogen has been used in the oxyacetylene welding of stainless steels to improve the weldability of the material. Chrome irons containing 0.24% nitrogen are readily welded[7] by both the arc and gas processes, and the welded structures exhibit more ductility and toughness than are obtained with low nitrogen metal. The nitrogen limits grain growth in the base metal adjacent to the weld.

Hydrogen.—Little information is available on the effect of hydrogen in the base metal and this is conflicting.[15, 16, 17] In welding, the chief sources are the gases in oxyacetylene and atomic hydrogen welding, and moisture in electrodes and atmosphere in arc welding.

Phosphorus.—Phosphorus in usual amounts is not usually held to exert any influence on the weldability of steel. All steels contain phosphorus, and it has been considered as an impurity. However, phosphorus is now added for the definite purpose of raising the strength of low alloy steels, particularly those of low carbon content. Of all the elements considered as impurities, phosphorus when properly used seems to have the least effect regardless of welding process used. Excellent welding results have been obtained with the low carbon, low alloy steels containing phosphorus.[14] Investigations have shown that with high rate of heat input per inch of seam and low welding speeds there may be a brittle zone adjacent to the weld due to phosphide network or constituent. This can be avoided by using per inch of seam the lowest rate of heat input consistent with sound welding for these low carbon steels containing phosphorus are practically insensitive as far as hardening is concerned. Phosphorus banding may be harmful in flash welds.

Sulphur.—Sulphur content of commercial steels is carefully controlled, and normally does not exceed 0.05% in steels for welding applications. Sulphur contents up to 0.05% have little detrimental effect on the weldability of the steels provided the sulphur is uniformly distributed. When the sulphides are segregated in bands, these zones contain as high as 0.12% sulphur, with the result that in fusion-welding processes the sulphides are balled up at the plate and weld junction, and even drawn out of the lamination, leaving voids that show up as defects at the junction in X-ray examination.[8]

If these bands occur near the surface, the defects cause stress concentration and premature failure in bend tests.[9] To eliminate this condition some users buy plate on the basis of a macro-examination, rejecting material with excessive sulphur banding.

Welds made by the submerged melt process in badly sulphur-banded plate suffered cracking, and investigation showed that with 0.04% average sulphur content the bands contained 0.12% sulphur. The cracks emanated[10] from the laminations, and when these laminations of high sulphur content are

absent, this cracking is not encountered. There is direct evidence that sulphur per se does not cause cracking or porosity in submerged melt welds or hand arc welds, for steels containing 0.09 to 0.24% sulphur are successfully welded commercially.[31] These steels are special steels for free machining qualities, and the sulphur is uniformly distributed as fine particles and the steel has a uniform macrostructure free from laminations or segregations. The manner in which the sulphur occurs[12] determines largely its effect on the weldability of the steel.

Oxygen.—Oxygen in the welds is considered a function of the welding rods or electrodes in conjunction with the particular process used. Little information is available as to the effect of oxygen in the base metal on its weldability. It is well known that the presence of mill scale on the underside of welded seams often causes porosity in the weld, resulting from reaction between the oxide and carbon in the molten weld metal. Nonmetallic inclusions in the form of oxides of iron, manganese, aluminum and silicon are often present in the form of complex silicate slags, and when present in the usual quantities do not cause difficulties in welding. The presence of large amounts of alumina causes porosity in welds, particularly in welds made at high speeds, as in automatic welding.

The strain aging phenomenon in low carbon steels is associated with iron oxide,[13] and is attributed to precipitation of iron oxide on slip planes induced by straining and aging. The phenomenon is accompanied by increased hardness and loss in notched impact resistance and ductility. It may be possible that cracking of base metal adjacent to the welds in some instances may be related to the strain-aging phenomenon.

It has also been suggested that the presence of FeO and MnO in the base metal was the cause of base metal cracks in oxyacetylene welded aircraft steels. The effect was attributed to the formation of H_2S and H_2O by reaction with the welding gases. Reduction of these oxides by the hydrogen in the welding flames produces zones suitable for hydrogen occlusion with subsequent embrittlement. Tests with specially refined aircraft steels show the same composition steel to be less sensitive to cracking. While it is difficult to definitely point to oxygen in the base metal as detrimental, it seems that its effect will depend chiefly on the metal with which it is combined, and this effect can be ascertained only by exhaustive tests on base metals containing various oxides that have been identified by fractional vacuum fusion methods. The cleaner the steel the more suitable it appears for welding application. Recent investigations have indicated that the presence of FeO and MnO in the base metal is largely responsible for the boiling of the molten puddle under the atomic hydrogen flame with possible entrapment of the gas to form surface or internal blow-holes in the solidified weld metal.

The detrimental effects of the non-metallic elements on the weldability of steels are the exception rather than the general rule, and when poor weldability occurs due to these elements, the steel is of questionable quality and is not representative of the class of steel. Wrought iron is a notable exception to this, as it contains definite amounts of slag of predetermined composition added for a particular purpose. Very good results have been obtained by some fusion-welding processes in fusion welding wrought iron.[19] Forge welding, pressure welding and resistance welding yield good results.

Effects of Other Factors on Weldability.—There are other factors that may affect the weldability of steels, such as surface coatings, high temperature strength and ductility, and grain size. Strictly speaking, the surface of any steel to be welded should be clean and free from foreign material such as paint, dirt, oil or grease.

Physical factors such as homogeneity and distribution of non-metallic inclusions have been discussed under effects of sulphur. The effect of grain size on weldability has been considered by some investigators, with the result that recommendations have been made that normalized, fine-grained high-tensile steels are more weldable than the same steels in the as-rolled condition. One investigator[18] concluded that a normalized fine-grained steel is necessary when welding low alloy steel over 1.18 in. thick, having the composition: carbon 0.18%, manganese 1.0%, silicon 0.4%, chromium 0.3%, copper 0.4%.

Improved tee bend results[26] have been reported on steels normalized before welding.

Other investigations[21] on medium and low carbon steels have indicated that inherent grain size of the base metal has little influence on the weldability.

Effects of Metallic Elements on the Making of Welds

In addition to carbon and manganese, steels for welding applications may contain one or more of the metallic elements mentioned under chemical factors. Some of them have definite properties and exhibit certain phenomena during welding which have nothing to do with their metallurgical properties, such as hardening power.

Carbon.—In oxyacetylene welding, increased carbon is accompanied by increased sparking and boiling or foaming in some cases. Usually the higher carbon steels have enough manganese and silicon present to quiet this action. Carbon in the base metal exhibits nothing unusual in arc welding.

Manganese.—Increased manganese content results in increased sparking in the absence of silicon. The sparking is attended with an infusible slag formation in oxyacetylene welding. Manganese is lost by volatilization and oxidation. The effects of high or low manganese are not manifest during arc-welding operations, and this element has little noticeable effect other than a possible increase in the fluidity of the slags formed during welding. This is particularly noticeable with steels of higher manganese contents (over 1.50%).

Silicon.—The addition of silicon (0.15 to 0.35%) to steels prevents the formation of CO and results in a so-called killed steel. Addition of smaller amounts partially suppresses the gas formation, and such steels are known as semi-killed. Steels designated as silicon-treated usually contain less than 0.10%. Silicon in the amounts usually occurring in steels for welding applications (0.15 to 0.35%) is a benefit rather than a detriment for all fusion methods of welding. Steel containing silicon in these amounts can be forge or hammer-welded but it is best that manganese contents of at least two times the silicon content be present to insure fusible slags.

Silicon is beneficial in oxyacetylene welding since it promotes reduction

of iron oxide and thus suppresses the formation of gas by reaction of oxides with carbon, insuring sound welds free from gas holes.

Its oxidation product, silica, combines with any iron or manganese oxides to form easily fusible slags. The presence of silicon suppresses sparking. On the other hand, the presence of high silicon in the base metal with low manganese results in a pasty slag. However, higher silicon steels usually carry enough manganese so that easily fusible slags are formed. Steels containing up to 1.0% silicon have been welded successfully, the silicon content producing no detrimental action during the welding operation. The best oxyacetylene welding rods contain silicon, making them of universal use for base metals with and without silicon.

Effects of Chromium, Molybdenum, Vanadium, Nickel, Copper, Aluminum, Titanium and Columbium on the Making of Welds

Chromium.—Chromium in the amounts ordinarily used in engineering steels exerts no detrimental action during welding by either the gas or arc processes. Sound welds can be made in steels containing up to 30% chromium. It is quite susceptible to oxidation, and once this is taken into account and the correct welding procedure adopted, no trouble due to chromium should be experienced.

Molybdenum.—Molybdenum is usually employed in conjunction with manganese or chromium, and steels containing this element are easily welded by the gas- and arc-welding processes. Molybdenum has no slag-forming characteristics and its presence is not noted during the welding operation.

Nickel.—Nickel steels containing up to 3.5% nickel and 0.80% manganese usually contain silicon up to 0.25%. Steels containing nickel melt quietly in the oxyacetylene process and offer no difficulty with either the gas or arc process when suitable rods and electrodes are used.

Copper.—Copper in amounts up to 1.0% does not affect the welding operation in so far as the making of the welds is concerned. Weld-cracking difficulties have been attributed to copper but this depends on the process used and the remaining composition of the steel.

Vanadium.—Vanadium is used in such small amounts that its presence is not usually recognized during the welding operation.

Tungsten.—Tungsten is seldom used in welding steels.

Aluminum.—Aluminum is ordinarily used as a deoxidizer and grain refiner. Properly refined steels that have been aluminum treated exhibit no adverse effects during fusion, though such steels may often contain residual aluminum or aluminum oxide. If too much aluminum has been used this shows up in the welding operation as an infusible scum that prevents free flowing, and usually results in porosity.[38] This is particularly noticeable in light-gage metal such as rim or barrel stock. Defective welds in both oxyacetylene- and resistance-welding operations have been traced to aluminum and alumina in the steel. Apparently[38] steels containing up to 0.2% Al. can be arc welded satisfactorily when mineral coated rods are used. There is no trouble with cellulose coated rod when a properly high current is used.

Titanium.—Few data are available as to the effect of titanium on the welding operation. In stainless steels its presence is not troublesome. Titanium is rapidly oxidized, and practically all of the element is lost in the fusion of the metal. This metal is added to stainless to prevent precipitation of intergranular carbide.

Columbium.—Columbium, like titanium, is added to stainless steel to prevent precipitation of intergranular carbide. It does not form an infusible slag and does not oxidize so readily as titanium in the welding operation. It exhibits no noticeable effect during the welding operation.

WELDABILITY OF PLAIN CARBON AND LOW ALLOY STEELS

Carbon steels have formed the bulk of the tonnage used for welding applications, and most of the information gained has resulted from studies on the welding of plain carbon steels. In these steels carbon is always associated with definite amounts of manganese, and any effects of the welding heat cycle may be attributed to the combined effects of the carbon and manganese. Both elements are strengtheners.

Fusion welding was applied to soft, ductile steels ordinarily used in boiler and pressure vessel practice and offered no obstacles in welding, after satisfactory filler metals and welding technique were perfected. The unit stresses imposed on the structures were moderate, and welding materials were available to match or exceed the properties of the base metal. Changes in service conditions in the form of increased unit stresses brought about a change in materials to be welded. Higher strength was obtained by increasing carbon or manganese or both, which together with increased thickness for severe service conditions imposed welding conditions that necessitated special materials and technique for the greater thicknesses. In order to minimize the thickness of base metal for use in high stress applications, high-strength steels were developed, and economies both in base metal cost and welding cost could be made by use of thinner materials, provided, of course, that they could be satisfactorily welded. Many special low alloy steels[1] were developed for welding applications, with the result that new technique and material were produced to meet the higher strength and to cope with difficulties such as cracking, which occurred in welding complex structures.

Some particular property of a steel made it more attractive from the engineers' viewpoint, with the result that isolated welding experiments were carried out comparing carbon steels and alloy steels to determine the relative merits of the steels from the welding standpoint. The tests were to determine the weldability of the steels that exhibited loss of ductility due to hardening in the rapidly heated and cooled areas adjacent to the weld. The chief factor, therefore, which affects weldability, is chemical composition of the base metal, and weldability tests are for the purpose of evaluating conditions under which sound joints free from undesirable effects can be secured. The chief undesirable property occurring in welded joints is lack of ductility, and welding was never widely accepted until a satisfactory test was introduced for evaluating the ductility of a welded joint. The free bend test filled this need, and more than any other single item influenced the acceptance of fusion welding by Code authorities.

Effect of Carbon and Manganese

In considering the effect of carbon and manganese on the weldability of plain carbon steels, only the heat effect on the base metal will be discussed. The general statement may be made that increasing carbon or manganese results in increased hardness with a given welding speed, and increase of welding speed (reduction in rate of heat input per inch of seam) with a given composition results in increased hardness in the auto-quenched zone immediately adjacent to the weld. A single welding layer will give maximum hardness and is indicative of the limitations that must be placed on plate thickness and welding speed for a given base metal composition.

Carbon is an effective hardener, and with the usual manganese content of 0.3 to 0.8% does not cause any difficulties when present in amounts up to 0.3%.

Manganese in the above amounts usually occurring in commercial plain carbon steels imposes no limitations when the carbon content does not exceed 0.30%. With increasing carbon and manganese contents, the auto-quench effect results in martensite formation, with loss in ductility and increase in hardness in the heat-affected zone.

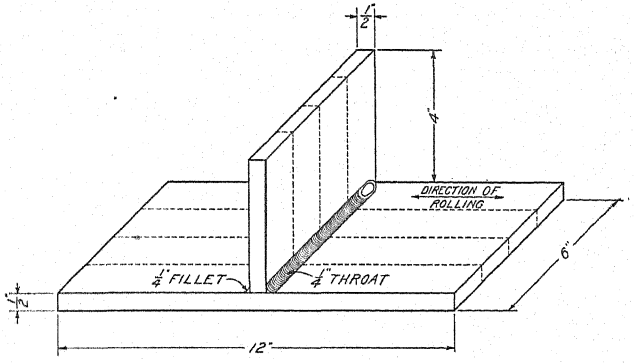


Fig. 1—Details of Welding for T-Bend Specimens

Automatic welding 175 amperes, 26 volts, speed 6 inches per minute, travel plates positioned for down-hand welding.

WELDABILITY TESTS

The committee on low alloy steels[1] discussed the relation of ductility to hardness, and data were given to show that ductility is the criterion rather than hardness and that hardness is not necessarily a measure of lack of ductility or a measure of weldability. Many authorities have limited weldability to a consideration of hardening and cracking. Summing up all discussions of weldability, ductility and toughness are the two properties that

are believed to be a measure of weldability. Hardness and ductility must not be taken as opposites, for steels of similar hardness do not possess identical ductility.

Several tests have been proposed and used to study the weldability of steels. They include not only the usual physical tests, tensile, bend, impact and nick-break, required by the Code authorities, but also several relatively new tests or applications of tests designed to show whether a certain base metal composition can be welded without deleterious properties across the welded joint. The following table lists the various tests which may be used singly or in combination, depending on just what information is desired.

Tests to Determine Properties of a Welded Joint or Weldability of the Base Metal

1. Hardness tests—Rockwell, Monotron, Vickers, Knoop.
2. Bend tests—plus hardness tests.
   Transverse free bend tests.
   Longitudinal free bend tests—longitudinal bead bend test.
   Tee bend tests. (Figs. 1 to 4.)
   Vee notch slow bend tests. (Fig. 5)
   Guided or restricted bend. (Fig. 6 to 8)
3. Tensile tests.
   All-weld-metal tensile.
   Transverse flat plate tensile.
   Longitudinal flat tensile—weld and heat-affected zones located longitudinally in center of specimen.
4. Notched bar impact tests—Charpy—Izod—Keyhole and Vee notches.
5. Cracking tests.
   Focke-Wulf rigid clamp test—for light-gage material.
   Reeves rigid clamp cracking test for heavy gages (Figs. 9 and 10).
6. Microscopic and macroscopic examination in connection with any or all tests.
7. Melting tests. Gas and atomic hydrogen welding.
8. Tensile impact test.

All of these tests, with the exception of the all-weld-metal tensile test, have been used either singly or in combination to show the heat effect of the welding cycle on the base metal. The all-weld-metal tensile will show whether or not the proper welding materials and technique have been used to insure weld metal of satisfactory strength and ductility. (See also Chapter 33A.)

1. Hardness Test

If the hardenability of a steel were the measure of weldability, it would be a simple matter to make a weld under service conditions and explore the hardness across the joint, or simpler yet, a bead could be laid on the steel under consideration and the maximum hardness in the plate determined. Several investigators have used this test in conjunction with other tests and have gathered considerable data. The chief drawback seems to be that there is no criterion of hardness that can definitely determine whether the steel has a high weldability rating. The test simply shows the hardness obtainable with a definite welding procedure. The results are comparative and provide no absolute measure of ductility.

As welding speed increased (rate of heat input per inch of travel decreased) maximum hardness in vicinity of weld increased for any given car-

bon and manganese content.[1, 3, 4] With manganese contents over 1.5% the auto-quench effect was very pronounced and cracking difficulties were encountered due to increased hardness and loss of ductility.

It has been shown that the hardening power of manganese[4] is one-fifth to one-seventh that of carbon, and that better comparison can be made by plotting hardness against % C + (% Mn/5 to 7). Straight-line curves were obtained, indicating the correctness of the hardening value assigned to manganese. Other investigators,[3,4] however, have shown that this is true for only a narrow range of carbon and manganese. This concept of carbon equivalents seems very useful and has since been applied by others. It

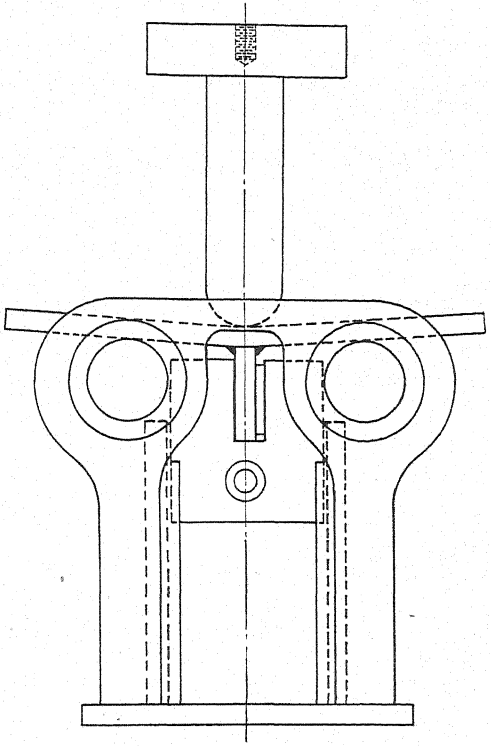
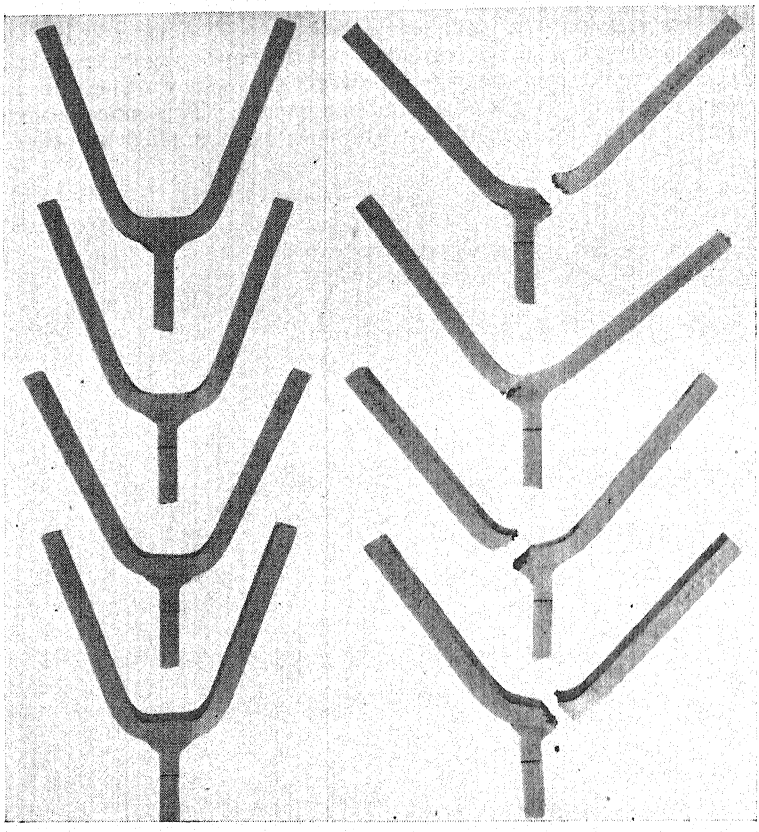


Fig. 2—Bending Jig for 1/2-In. T-Joint Specimen

shows relation to plate hardness as measured under a bead rather than ductility which is the prime consideration. Attention is also called to the formula in Table 5, Standard Qualification Procedure, Chapter 29, which shows the relationship between manganese, silicon and carbon, in determining the grouping of steels in so far as welding procedure is concerned.

In a study of the weldability of casing steels[5] in thicknesses not exceeding 1/2 in., it has been shown that acceptable welds in the as-welded condition can be obtained in Grade "C" casing pipe containing 0.32 to 0.42% carbon and 0.60 to 0.90% manganese. With carbon and manganese contents beyond these limits, preheating or stress relieving is essential to minimize

hardness and loss of ductility. The same compositions in thicknesses greater than $^1/_2$ in. would result in cracking. In a report on the study of the heat-affected zone[6] in steels containing 0.29 to 0.49% carbon and 0.67 to 0.93% manganese, it was concluded that the effect of carbon on the



Normalized As Rolled

Fig. 3

properties of the heat-affected zone is dependent on base metal thickness and rate of heat input per inch of arc travel, or rate of weld quench. Detrimental properties in the heat-affected zone due to carbon and manganese content can be eliminated by insuring that a temperature of 300–400°F. is maintained in the first pass and each succeeding pass until the following pass is made. On heavy sections of an inch or more in thickness a preheat of 575°F. is recommended to prevent the initial deposits from cooling below 300°F.

Single bead weldability tests[22] carried out on S.A.E. 1020 and 1045 steels showed maximum Vickers hardness values of 190 and 320, respectively, for $^1/_2$-in. plate, and 230 and 520 for $1^1/_2$-in. plate. These tests show effect of mass on degree of weld quench. Time vs. temperature relationships taken on bottom plate surfaces did not furnish an index of hardenability. Judg-

ing from these hardness tests, S.A.E. 1020 is weldable in both thicknesses, whereas S.A.E. 1045 would be considered weldable in $^1/_2$-in. plate only under the conditions of heat input used in the experiments. Vickers hardness of 350 was placed as the limit of weldability.

The single bead test was also used by other investigators[20] to provide comparative data using a standard welding technique. The single bead induces maximum hardness for fixed conditions of welding and plate thickness. Any cracking caused by a single bead cannot be repaired by any annealing effect of subsequent layers; hence the single bead was considered

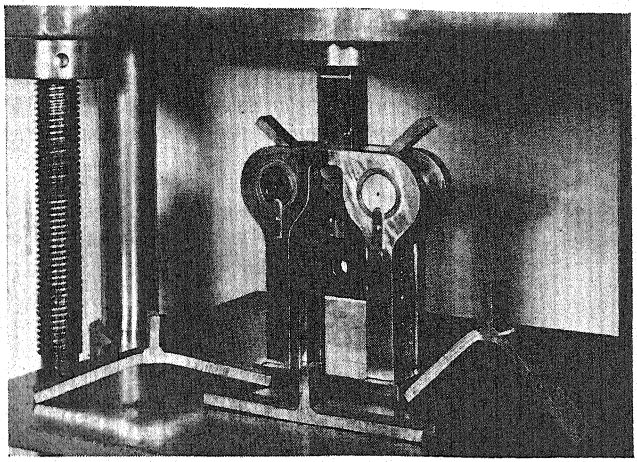


Fig. 4—Bending a Specimen in a T-Bend Jig

most desirable. These investigators studied many plain carbon and low alloy steels by determining the maximum hardness under a single bead, and found that weld hardness tests should be carried out under exactly the same welding conditions as encountered in practice. The weld-induced hardness depended not only on the capacity of the steel for hardening, but also on the many variables associated with welding technique and the dimensions of the parts used in the test.

Under fixed welding conditions, low alloy steels showed higher welding hardness than plain carbon steels at equal carbon contents between 0.10 and 0.50%. This is to be expected since alloys increase hardening tendency. When weight reductions are desired, low carbon complex alloy steels offer distinct advantages over plain high carbon steels with respect to weld hardening. At equal and higher yield points, such alloy steels show lower weld hardening, better retention of toughness at low temperature and, due to low carbon, they can be expected to have better forming properties.

Hardness tests carried out by the various investigators have established beyond question that under fixed welding conditions the hardness increases as carbon and manganese increase, and that for any given base metal composition the hardness increases as the welding speed increases. The tests also show that as their hardness due to welding increases low carbon, low alloy steels lose their toughness less rapidly than plain carbon steels. Some

data have been obtained from the hardness test which show some relation between hardness and ductility for a given type of steel. With a steel of unknown properties other than composition, the test does not reveal any information other than hardness; hence will give no real indication of how the steel will perform in a complex welded structure. The hardness test is a complementary test to be correlated with other tests.

2. Bend Tests Plus Hardness Tests

In making a transverse free bend test on a specimen cut transverse of the weld, uniform elongation in the outside fibers is obtained when the weld metal, heat-affected zone and unaffected plate are of about the same hardness. When a large degree of hardening has taken place in the heat-affected zone, this zone elongates little, with the result that the test gives little information as to the ductility across the weld zone. Ductility of the weld metal is the main property measured by the transverse free bend

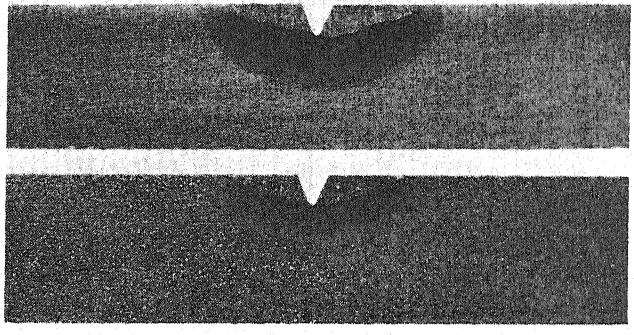


Fig. 5—Bead Weld Notched-Bar Specimens (0.394 x 0.394 x 2.165 in.)

test. In order to obtain information regarding the effect of the heat cycle on the ductility of the heat-affected zone as well as the weld metal and base metal, longitudinal specimens consisting of the weld in the center bounded by the heat-affected zones and plate metal are used (Fig. 5). When bent as in the free bend test or in a jig (Fig. 8) all zones are caused to elongate, and the ductility of the hardened zones as well as that of the weld metal can be measured. This test can be applied to butt welds or to plate specimens on which a bead of weld metal has been applied, to produce the hardening effect, and then the bead removed flush with the plate surface. This test is known as the bead bend test.

Jig bead bend tests[21] were carried out on a series of steels with increasing carbon and manganese contents. A correlation of hardness surveys and bend elongations indicated a Brinell hardness of 250 in the heat-affected zone as a safe limit, with 20% minimum elongation in the slow bend test. This maximum hardness is conservative, as will be seen from the work of other investigators, but is probably correct if capacity for deformation of the welded joint is considered. The maximum tolerable hardness is obviously determined by the application. Steels were rated by the minimum

preheat required to avoid sensitivity. A steel with high merit rating, therefore, possessed a high ductility and low minimum preheat to avoid sensitivity or freedom from cracking.

The longitudinal bead weld slow bend test was also advocated by a European investigator[27] who recommended it for structural steels with the additional provision that steels over 1.18 in. thick be normalized before welding to avoid brittle fracture. If the steel bends with a ductile fracture, characterized by progressive failure, it indicates more satisfactory weldability.

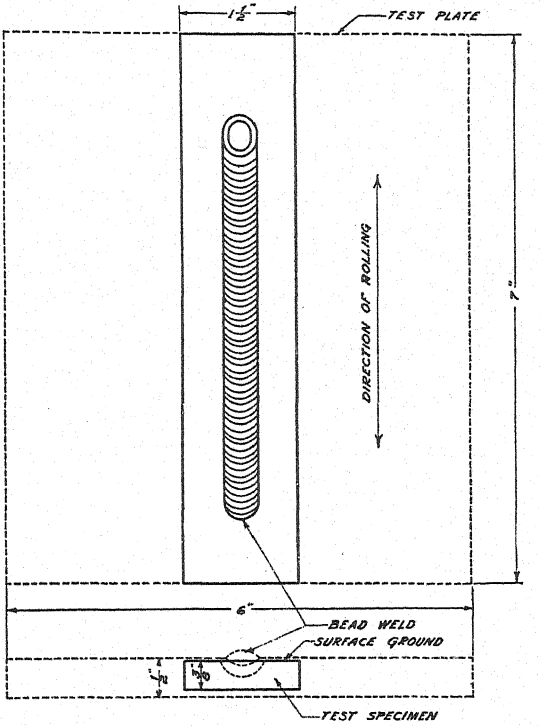


Fig. 6—Details of Longitudinal Bead Weld Slow Bend Specimen

Further applications of this test by other investigators[25] indicated that it was not sensitive to changes in welding technique (heat input and speed of welding) when applied to low carbon steels. Failure to show a high rating in this test would label a steel as definitely inferior for the welding technique used.

Tee Bend Test.—The tee bend test[26] is a special form of bend test developed to determine the weldability of steels when fillet welded into structural designs. When a steel must be welded at atmospheric temperatures of +10°F. and above without preheat or postheat as in ship structures, and the welded joints must be capable of deforming in service without losing their water tightness, the tee bend test is considered effective in determining the weldability of the steel.

Specimens for this test (Fig. 1) are prepared from 1/4, 1/2 or 3/4-in. plate. A 12-in. by 24-in. by t piece of plate has a 4-in. by 12-in. by t piece of plate attached to it by fillet welds of 1/2 t size. These fillet welds are continuous welds made in one pass. Specimens 1 1/4 in. wide are cut from the assembly and bent in a special jig (Fig. 2). The test is evaluated by angle of bend and maximum load. Tests[25] on twenty steels showed a general relation between tee bend performance and carbon content. Other factors such as laminations, however, have an effect on this test and cause failure at low bend angles. Other investigators[26] showed that normalizing before welding has considerable effect on the tee bend results (Fig. 3). Steels welded in the as-rolled condition will fail at low bend angles, whereas the same steel normalized before welding will pass the test satisfactorily. This indicates that grain size is a factor in the tee bend test.

The tee bend test is somewhat critical in that the size of the fillet weld for any thickness has a large effect on the bend results. For instance, a tee assembly in 1/2-in. plate with 1/4-in. fillets will fail in the test, whereas with a 5/16-in. fillet the steel will pass the test satisfactorily.

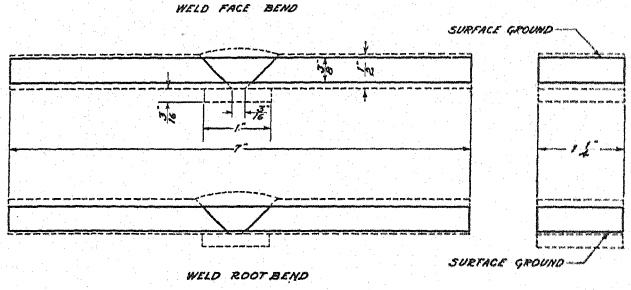


Fig. 7—Face Bend and Root Bend Specimens

Vee Notch Slow Bend.—This test is usually carried out by depositing a bead on the surface of the plate to be tested, from which transverse specimens 0.394 in. by 0.394 in. by 2.165 in. are machined and notched (Fig. 5) so that the apex of the notch is tangent to the fusion line or junction of weld deposit and plate. The specimens are then bent with the notch down in the jig shown in Fig. 8. The angle at maximum load is noted. As in the tee bend test, plate quality affects the results, laminated or woody structure resulting in premature failure. Correlation of vee notch slow bend and tee bend results is quite good with the exception of some results on low carbon steels.[25] In this test failure usually occurs at maximum load which may be taken as a criterion for energy absorption in the bend test for those specimens which fail at or near the maximum load.

The vee notch slow bend test has been applied[32] to specimens quenched to the same hardness as would be obtained from a welding application. The scheme recommended uses the rate of cooling as a basis but does not require its direct measurement. The thought is that ductility of a steel adjacent to a weld is a function of the steel and the rate of cooling, and that the rate of cooling for a given steel may be indirectly measured by hardness. The quench effect or rate of cooling of the heat-affected zone is defined by

the hardness at the center of a drastically quenched cylinder of such diameter that the center hardness is the same as that obtained in the heat-affected zone. This then becomes the equivalent bar diameter. Specification for weldability would read, "the minimum notch bend elongation of a flat bar of the steel in question shall be not less than, say, 30% after the sample shall have been heat-treated by continuous cooling to a hardness equal to or greater than that of the center of an ideally quenched cylinder of a specified diameter." The concept is a little difficult, but is a good proposal for specifying weldability on the basis of a ductility test of metal having hardness the same as that resulting from a definite welding procedure.

The vee notch slow bend test applied to a series of nickel steels[33] gave results comparable with tee bend results and showed a general interrelation-

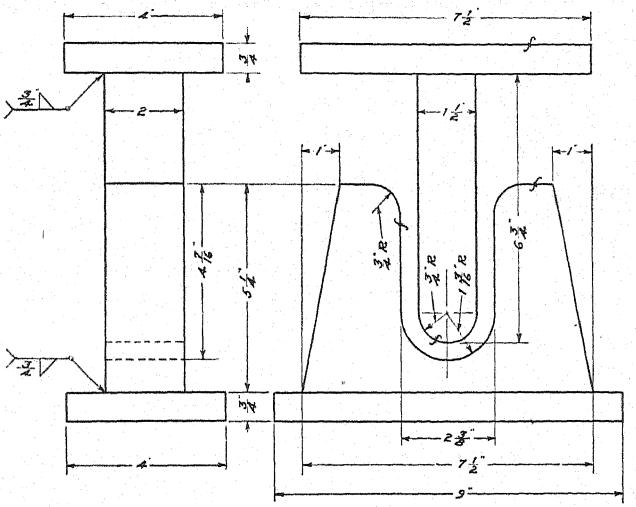


Fig. 8—Guided Bend Test Jig

ship between the tests. In these tests there was also correlation between the vee notch slow bend results and maximum Knoop hardness numbers, showing that for a given type of steel the ductility of the heat-affected zone bears a close relationship to hardness.

3. *Tensile Tests*

(*a*) *All-Weld-Metal Tensile.*—The all-weld-metal tensile test is not primarily a weldability test except that it will show the effect of base metal composition on the tensile properties of the weld metal. This effect is particularly noticeable in the welding of low alloy steels with either alloyed or unalloyed welding compositions and is dependent on the amount of base metal melted into the weld. The test is very important and is necessary for the determination of the correct welding composition and technique to be used for any given type of base metal.

(*b*) *Transverse Flat Plate Tensile.*—This type of tensile test, usually of the reduced section design, affords information as to the strength of the joint compared with that of the base metal. This has been used to determine the relative yield points of the base metal and weld metal.

(*c*) *Longitudinal Flat Tensile Including Weld, Heat-Affected Zones and Plate Metal.*—This test, although not universally used, is very useful in investigating by one test the relative ductility of the weld metal and of the heat-affected zones. This test has been used[35] to determine the presence of cracks resulting either during the welding operation or from applied stress and is able to distinguish between cracks formed under either circumstance. The test is very useful for determining the correct combination of welding composition and plate to insure more uniform properties across the joint for a given welding technique. As a weldability test, this type of tensile test has the advantage over other tests of providing information not only as to plate hardening and loss of ductility but also as to the welded joint as a whole.

4. Notch Impact Test

The notched bar impact test has been used[23] to evaluate the toughness adjacent to welds by means of impact fractures through the heat-affected zones. These values were compared with unwelded base steel which had been heated and quenched to give structures similar to those in the heat-affected zone. This test is known as the weld quench test, and was recommended (1) for the determination of a suitable composition for foolproof welding, (2) for the determination of unsuitable compositions for good weldability, with the further condition that such steels will require preheating and possible postheating for successful welding. It was claimed that this test can be applied to the steel before any welding is done, and at low cost, and that it separates steels into sensitive and insensitive groups. Further extension of the test to the more sensitive steels may lead to a classification of weldability on the basis of preheat required.

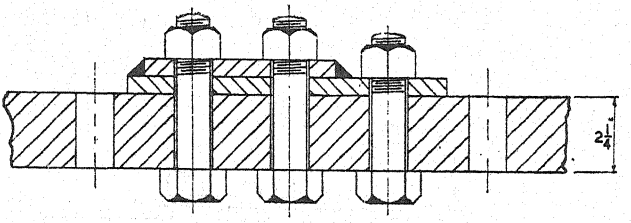
The weld quench test provides a specimen whose entire structure is presumably the same as that of the narrow zone lying between a tough weld metal on one side and tough plate on the other. It is natural to expect some difference in impact behavior of the same type of structure between the condition when it comprises the entire volume under the notch and the condition when it forms only a small layer between two tough structures.

Transverse weld impact specimens from several welding steels[24] were notched so as to cause fracture through the heat-affected zone. Impact results were compared with those of unwelded plate. The steels were grouped according to hardness of heat-affected zone, although it was recognized that steels of different compositions may have different toughness or ductility for equivalent hardness. The test indicated effect of weld heat treatment on notch sensitivity.

Tests carried out on a series of nickel steels[33] showed a similarity in type of fracture in tee bend and notch impact tests. Except for laminated plate it may be said generally that high and ductile vee notch impact values predict good tee bend and vee notch slow bend performance, and, conversely, brittle vee notch values indicate premature failures in tee bend and vee notch slow bend tests.

5. Cracking Tests

One of the main problems in welding high-tensile steels is the prevention of hot cracks in the weld metal and cold cracks in the base metal. Cracking tests have been developed to determine whether or not the steel cracks when welded under conditions of high mechanical restraint. In the Focke-Wulf or Muller tests[36] designed for aircraft steels, small pieces of light-gage metal are rigidly clamped and the seam welded continuously. The welded



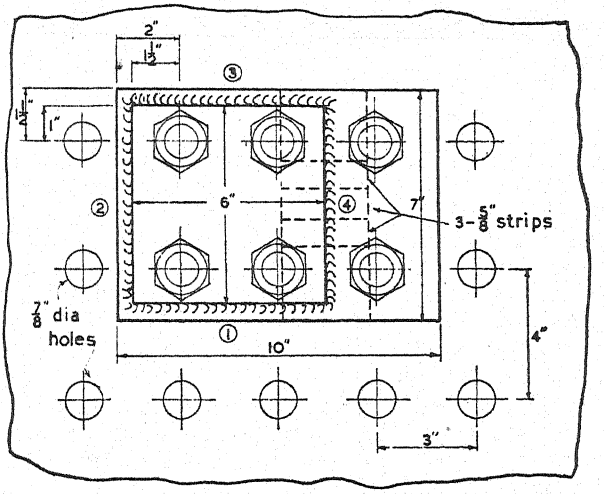
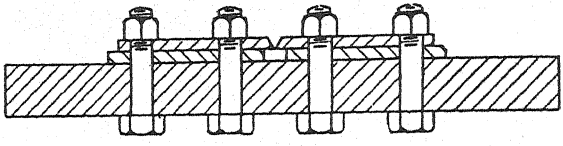


Fig. 9—Reeve Cracking Test Equipment. ¾-In. Bolts in ⅞-In. Holes Sequence of Welding Indicated by the Figures

section is then examined for cracks, particularly in the base metal immediately adjacent to the weld. This is a sensitivity test and gives no information regarding the physical properties of the joint. These steels of light gage are air hardening and, because of the thinness and the technique used in welding, can be welded without preheat. Some heats of steel seem more sensitive than others to cracking, and the Focke-Wulf test is used to single out the more sensitive steels.

The chief cause of hard cracks in the base metal is hardening with loss

of ductility, cooling rate and degree of restraint being the determining factors. The Reeve test was developed in England for determining whether or not a steel would crack under a certain welding procedure and a high degree of restraint. The test consists in making fillet welds in overlapping plates (Fig. 9) which are bolted to a heavy base plate. After welding, the fillet welds are sectioned and examined for cracks. This test has been accepted as standard by the British Engineering Standards Committee. In order to have a common basis on which to compare the weldability of complex alloy steels, British investigators[14] used the concept of carbon equivalents. A study of the weldability of several low alloy steels based on the Reeve test, using $^1/_2$-in. plate and 0.045 sq. in. fillets and hardenability coefficients for the various alloys, showed that with ordinary electrodes the hardness of the heat-affected zone should not exceed 350 Vickers hardness



— MODIFICATION OF CRACK TEST FOR BUTT WELDS —

Fig. 10—The Reeve Specimen[36]

if cracking is to be avoided. With the same conditions of fillet size it was found that 0.45% equivalent carbon was the maximum allowable if the steel was to be generally weldable. Higher equivalent carbons may be welded if fillet size is increased to provide greater heat input. A table is given of recommended fillet sizes to insure a maximum weld hardness of 350 for different carbon equivalents. This test does not yield any information as to ductility in the heat-affected zone, and is more applicable to fillet welds although it has been applied with some success to butt welds in the so-called modified Reeve test.

Cracking in the base metal hardened zone is more prevalent with some types of electrodes than others. Electrodes depositing soft weld metal with carbon not over 0.08%, manganese not over 0.30%, and silicon not over 0.05% reduce cracking tendency. Austenitic electrodes also reduce cracking tendency. It is possible to weld with austenitic electrodes and have no cracking with hardness values up to 600 Brinell. This would indicate that cracking may be avoided by using electrodes producing weld metal with a yield point not over 30,000 psi. Other factors that reduce tendency to cracking are preheating, and a high rate of heat input per inch of travel of the welding arc or flame.

7. *Melting Tests—Oxyacetylene and Atomic Hydrogen Welding*

This test consists of melting the surface of the steel by the oxyacetylene or atomic hydrogen flames without the addition of filler metal. It is usually applied to light gages. In aircraft steels it indicates sensitivity to

cracking. In non-hardening steels this test determines weldability by the smoothness of the bead and its freedom from visible porosity.

8. Tensile Impact Tests

This test consists of breaking a specimen in tension by means of impact or suddenly applied loads. The specimens are usually round with an 0.5-in. to a 4.0-in. parallel section, the length depending on the diameter. The specimen may also be a structural design such as a tee to test fillet welds. The test is particularly applicable to ballistic structures which have to withstand suddenly applied loads.

The consensus of opinion seems to be that 0.15% carbon or 0.20% at the most should be the limiting carbon content in low alloy steels for welding applications. Maximum hardness and loss of ductility in the heat-affected zone are related essentially to the carbon content, the alloying elements having secondary effects which are significant, depending on amount added. When small amounts of alloying elements are added, the effect is to increase the yield and strength somewhat in proportion to the amount added. For a detailed list of several commercial low alloy steels, reference should be made to the report of the Committee on Low Alloy Steels.[1]

Specification for Weldability

Numerous weldability tests have been conducted by several investigators, and they all show that weldability tests cannot be discussed independently of welding conditions. In many cases the tests are specific in that they employ joints and technique simulating those used in a particular construction. One such test is the tee bend test employing fillet welds, a test that was developed primarily to evaluate the performance of steels used in ship construction.

The most promising tests are those which show some correlation with each other in determining the effect of welding heat on the hardening and loss of ductility, or, conversely, in picking out steels that show the least damaging effect for equivalent physical properties.

Those tests evaluated in terms of ductility show the best correlation and afford information as to the ability of the welded structure to withstand applied stresses even up to the point of plastic deformation. It is evident that all of the tests should be applied to specimens welded with the same procedure preferably one which insures a rapid cooling rate.

Tests Based on Ductility Measurements

Longitudinal Bead Slow Bend Test.—This test is simple and is carried out by applying a bead to the metal under test and grinding off the reinforcement (Fig. 6). After gage marks are applied, the specimen is bent either by a jig (Fig. 8) or preferably by free bend, and the elongation measured at sign of first crack. Hardness measurements should be made on the heat-affected zone. A minimum elongation of 20% should indicate good weldability.

Tee Bend Test.—This test is evaluated by measuring angle at maximum

load when tested in a standard jig (Figs. 1, 2, 3 and 4). A minimum angle of 60° insures a steel of good weldability.

Vee Notch Slow Bend Test.—A steel welded under the same heat conditions as for the tee bend test should show a minimum bend angle of 20°. This test may also be evaluated in terms of ductility by measuring the distance between the top edges of the notch before and after bending (Fig. 5).

Weldability of a steel is, therefore, dependent greatly on the hardenability of the steel, with attending loss of ductility. In order to avoid brittle structures in the heat-affected zone, the cooling rate shall be such that practically complete transformation of austenite to pearlite can take place. Data have been presented to show that much information can be obtained from S-curves[37] (isothermal diagrams) or derived curves covering transformations at a continuous cooling rate. The S-curve data will show for a given steel whether low or high preheat is necessary to insure a pearlitic structure. It will also show that with a steel such as S.A.E. 4140, welding must be carried on in the vicinity of 700°F. to avoid martensite formation. The optimum transformation temperature level and the time for holding at this temperature to insure a tough structure can be obtained from the S-curves. While it is possible to obtain from such curves the maximum cooling rate that will insure tough and ductile structures, it is difficult to translate this information into welding practice. In the first place there are some steels that exhibit practically no hardening tendency, yet they may be entirely unsuitable for welding. Ductility tests are necessary to pick out such steels. On the other hand, welding technique and conditions are exceedingly variable. Plate temperatures vary greatly between winter and summer, indoors and outdoors, and in heated and unheated shops. Controlled cooling other than by ordinary preheat would be difficult on complex structures. The first information necessary is whether or not a steel will harden and what loss of ductility attends this increase in hardness. The logical procedure would be to make a bead weld under the conditions of welding and electrode size adopted and apply some of the ductility tests such as longitudinal bend, vee notch slow bend, etc. Also, hardness explorations should be made across the weld zone. If the mean hardness in the heat-affected zone is less than 350 Brinell it is quite probable that such a steel could be welded without cracking. A preheat of 200-500°F. would insure minimum hardness and maximum ductility in the heat-affected zones, the degree of preheat being higher for low welding heat input and lower for high welding heat input. Where hardness greater than 350 is obtained in the bead welds, preheat and possibly postheat are necessary to insure a structure of maximum toughness.

The concept of equivalent carbon content offers a possible means of appraising to some extent the weldability of the steel. Data are available to show that for several types of steels, the maximum hardness is proportional to the equivalent carbon content, and that with normal conditions of heat input, steels with equivalent carbon contents up to 0.45% can be welded without cracking. Data are also available[33] to show that for a series of steels of the same class there was a close relationship between Knoop hardness and ductility of the heat-affected zone. Furthermore, in these same steels there was a close relationship between equivalent carbon content and ductility as measured by tee bend tests and vee notch slow bend tests. Maximum weldability occurred when the total equivalent carbon content

did not exceed 0.42% and the element carbon did not comprise more than one-third of the total equivalent carbon. It would seem, therefore, that the concept of equivalent carbon could be applied to unknown steels or at least to a series of the same type to get first-hand information as to the hardening properties and probability of cracking. For the final answer, ductility tests must be made on heat-affected zones resulting from welding technique identical to that used in practice. Weldability cannot be discussed independently of welding conditions.

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CHAPTER 4 A

FUNDAMENTALS OF ARC WELDING*

Mechanism of Weld Metal Deposition, Circuit Characteristics and Arc Stability, Blow-Holes and Slag Inclusions in Weld Metal, Effect of Base Metal Compositions and Properties on Arc Stability and Weld Properties, Striking, Maintaining and Breaking the Arc, Arc Voltage and Length, Speed of Welding, Control of Residual Stresses, Control of Shrinkage, Control of Warping, Stress-Relieving Methods.

THE Process Chart, Chapter 42, shows that arc welding is one of three major welding processes which do not require pressure to complete the weld—arc welding, gas welding and Thermit welding. This basic fact greatly simplifies the equipment required and reduces the initial cost of an installation. In manual welding processes, it also permits the equipment to be taken to the job, thus introducing an element of flexibility in the utilization of the three major processes mentioned which is only possible, to a limited extent, in those "Pressure Processes"—forge welding, resistance welding and pressure Thermit welding, also shown in this chart, wherein both heat and pressure are required to produce a weld.

As a group, arc welding, gas welding and thermit welding are classified as fusion welding in Specifications, Codes and Rules governing the construction of welded products. All have identical basic design requirements for weld properties. The Procedure Qualification tests required to demonstrate these properties are also generally the same. See Chapter 29. Metal arc welding consists essentially of a localized progressive melting and flowing together of adjacent edges of "*base metal*" parts by means of temperatures of approximately 10,000°F. of a sustained electric arc between a metal electrode and the base metal.

In metal arc welding, the melting electrode furnishes the "*filler metal*," the arc being maintained by manually or automatically feeding the melting electrode at a uniform rate toward the base metal. In atomic hydrogen and carbon arc welding, filler metal in wire or rod form may or may not be manually or automatically fed into the arc and melted simultaneously with the base metal.

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* This Chapter was originally prepared for the 1938 edition of the Handbook by James W. Owens. It has been revised by a committee consisting of James W. Owens, Fairbanks Morse & Co., *Chairman*; G. E. Doan, Lehigh University; C. H. Jennings, Westinghouse Elec. & Mfg. Co.; L. J. Larson, Consulting Welding Engineer; Bela Ronay, U. S. Naval Academy, Engineering Experiment Station and W. Spraragen, AMERICAN WELDING SOCIETY.

That portion of the base and filler metals which has been melted during the welding operation is termed "*Weld Metal.*" In the carbon arc and atomic-hydrogen processes, weld metal consists entirely of base metal, except when filler metal is also melted in the arc. In the latter case the weld metal will be a mixture of base and filler metals. In metal arc processes, weld metal may be either filler metal (unadulterated by the base metal), or a mixture of base and filler metals, depending on the depth of penetration into the base metal.

Shielded and Unshielded Processes

The ideal weld is one having the same properties as the parts joined. Such a weld, when made by an arc-welding process, can only be obtained by effectively protecting the molten filler metal from the oxidizing and nitrogenizing effects of the air *during the entire range of liquefaction and solidification.* When molten metal is not protected from atmospheric contamination, it absorbs a harmful volume of nitrogen and in addition suffers partial oxidization. Weld metal which is thus contaminated is brittle even though it may have a tensile strength of 50,000 to 60,000 psi. See Table 1, Chapter 4E. However, it has been and is being satisfactorily and economically used in many types of products. It should not be used for:

(*a*) Butt joints, in general;
(*b*) Types of joints having a high residual stress—Figs. 8, 9 and 10; and
(*c*) Highly stressed products, or products subjected to fatigue and impact stresses, severe corrosive conditions or high operating temperatures.

Arc-welding processes wherein molten filler, weld and base metals are effectively protected are classified as *shielded* processes to distinguish them from *unshielded* processes wherein no protection, or only partial protection is afforded. Whether a process can be classified as a shielded or as an unshielded process will depend on whether the physical properties of welds made under a carefully conducted procedure qualification test can comply with the requirements given in the Specification, Code or Rules under which the test is made. The table referred to in the preceding paragraph gives the general range of these requirements for shielded and unshielded arc-welding processes.

Chart—Fig. 1 is an extension and elaboration of the arc-welding processes chartered in Chapter 42. The term "*Covered Electrode Welding*" embraces all processes wherein shielding is accomplished by combustion, vaporization and melting of the several ingredients of the covering applied to the wire core of the electrode. The term "*Taper Shielded Welding*" is used to cover all processes wherein a ribbon or cord is independently and automatically fed into the arc zone and functions in a similar manner to the coverings on covered electrodes. The term "*Gas Shielded Welding*" is applied to those processes wherein the arc zone is surrounded by a reducing or inert gas supplied from an independent source, and the term "*Flux Shielded Welding*" is used for all processes wherein a flux in the form of a paste or powder is placed on or in the joint ahead of the arc, surrounds the arc and is wholly or partially vaporized or melted as the welding operation proceeds.

Alternating and Direct Current Processes

In direct current bare electrode welding of mild steel, the heat developed at the positive terminal (anode) is greater than that developed at the

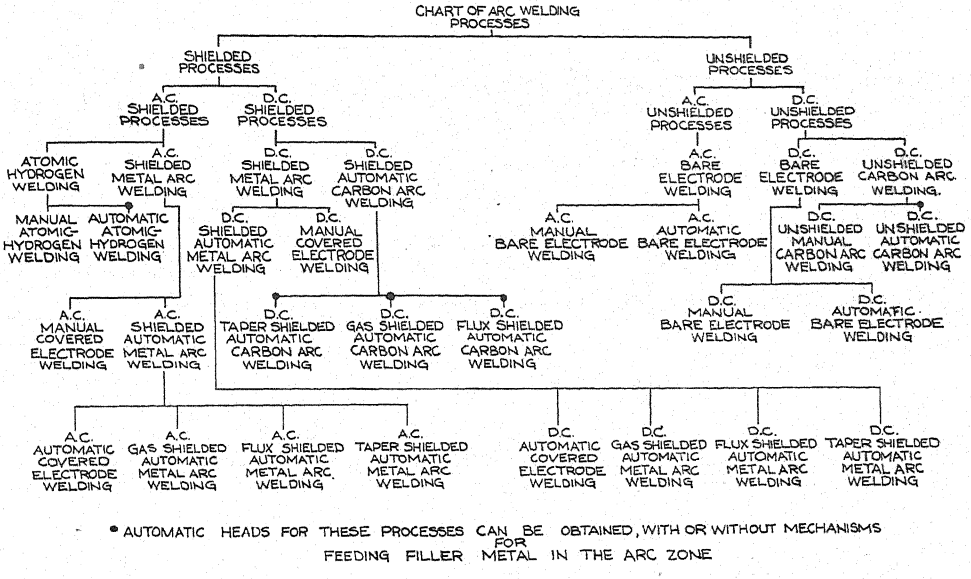


Fig. 1—Chart of Arc-Welding Processes

negative terminal (cathode). Therefore, in view of the greater heat absorption and conduction capacity of the work, it has been found desirable in the bare electrode welding of carbon steels to make the work positive and the electrode negative in order to facilitate consistent fusion. Moreover, it is difficult to hold an arc with bare wire using reversed polarity.

In the case of some of the early covered electrodes, it was found that consistent fusion was facilitated by reversing the polarity.

Early experiments with a.c. bare electrode metal arc welding indicated that a higher open circuit voltage (than required for d.c. welding) was necessary in order to prevent an extinguishing of the arc every time that the current passed through zero during each cycle. More recently covered electrodes have been developed for use with a.c. current and with open circuit voltages which are not only considered safe from an operating standpoint, but which give good heat distribution. It should be noted, however, that devices have been developed which afford protection from the danger referred to, and arc continuity can be obtained with bare electrodes by increasing the volume of ionization through the use of higher current values. Furthermore, ionization may be further increased and the open circuit voltage decreased by the use of suitable light coatings on otherwise bare electrodes, and the use of types of coverings on covered electrodes which provide a projecting refractory crucible at the tip of the electrode.

Even with low currents and bare electrodes, a low open circuit voltage may be employed, provided the arc is stabilized by means of a high frequency sparking circuit.

Alternating current is used in atomic-hydrogen and double carbon arc welding because it is essential that the electrodes be consumed at a uniform rate. On the other hand, in those carbon arc processes wherein only one carbon electrode is employed, direct current with straight polarity is used for the principal reason that by making the electrode the negative pole there is no carbon pickup in the weld. It is also difficult to hold a stable arc with reversed polarity. Moreover, the electrode is consumed at a lower rate than it would be if alternating current were used or if it were made the positive pole. This method of polarizing a single carbon arc renders the electrode tip the hot cathode whereby a steady arc is maintained with a constant power input at the arc.

Alternating current is usually preferable when magnetic blow causes serious arc instability. Magnetic blow is particularly annoying when welding in restricted places and corners, and when high currents, as required in thick sections, are used. The resulting effect of magnetic blow is an erratic arc causing blow-holes and slag inclusions in the weld at the points of disturbance. On the other hand, direct current may be preferable for many types of bare and covered non-ferrous electrodes, and when ferrous welds are to be made in the horizontal, vertical and overhead positions.

Covered electrodes are obtainable for either alternating or direct current or for both.

Mechanism of Weld Metal Deposition

The mechanism of weld metal deposition is relatively simple in those *shielded and unshielded processes (atomic-hydrogen and carbon arc), wherein the filler metal is independently fed into an uninterrupted arc stream* which progressively melts both the base metal (or the previously deposited weld metal) and the end of the filler metal in contact with the arc. When welding in the flat position with these processes, molten globules of filler metal drop into the molten base metal by the force of gravity, whereas in horizontal, vertical and overhead welding, surface tension attracts the molten globules to the molten base or weld metals into which they flow.

In *shielded and unshielded metal arc processes* a number of forces are involved in varying degrees, in the transfer and retention of molten filler metal. Among the forces suggested are the following:

1. Vaporization and condensation.
2. Gravity.
3. Pinch effect.
4. Surface tension.
5. Gas stream from electrode coatings.
6. Pressure on the cathode spot of the arc.
7. Expansion of gases in the metal at the electrode tip.

The phenomena of transfer of metal in metal arc welding may be divided into two parts:

1. The transfer of the metal from the electrode to the molten pool and
2. The retention of the metal in the pool.

Forces which are important in *retaining* the metal after it reaches the pool may be of little or no importance in *transferring* the metal from the electrode to the work. In overhead welding, surface tension retains the metal in place and must be sufficient to overcome the force of gravity or molten metal will drop out of the pool. Hence, it is imperative to limit the size of the pool in overhead welding. In flat welding surface tension and gravity both act to retain the metal in the pool. In horizontal, vertical and overhead welding, surface tension tends to hold the metal in place, whereas gravity either aids or hinders depending upon the position. In vertical welding, the direction of welding (upward or downward) is also involved.

Vaporization and Condensation.—The energy available in the arc is sufficient to vaporize only a small percentage of the total amount of metal passing across the arc. However, of that portion of the metal at the end of the electrode which is vaporized by the intense heat of the arc, some is condensed in the pool on the work which is at a much lower temperature than the tip of the electrode. Much of it escapes to the surrounding air. Some metal is transferred from electrode to work with all types of electrodes, in all positions and with both a.c. and d.c. current.

Gravity.—In the transfer of the metal across the arc gap it does not appear that gravity is an important factor. The rate of metal transfer, as measured by the melting rate of the electrodes, is practically the same when welding in the overhead as when welding in the flat and horizontal positions.

Pinch Effect.—The high current passing through the molten globule at the time of the short circuit results in a radial compressive force which tends to pinch the molten globule and detach it from the electrode. Authorities differ as to the magnitude of the force and the amount of metal transferred in globular form. The pinch effect aids only during short circuits. Moreover it is not effective in inert gases.

Surface Tension.—Surface tension is no doubt a very important factor in retaining the molten metal in the pool on the work. However, in transferring the metal across the arc gap when no short circuit exists it is difficult to see that surface tension plays any part. When a globule short circuits the arc, surface tension draws the metal into the molten pool but such a force has no tendency to project any particles of metal through space.

Gas Stream from Electrode Coatings.—The velocity of the gas stream produced by certain types of coatings, undoubtedly tends to give the small particles in the arc gap a velocity in the same direction. Even with electrodes having little gas-producing coatings, the metal passes across the arc gap in the form of many small globules which are traveling at a considerable velocity. It therefore appears that some other force is chiefly responsible for the transfer of the metal across the arc.

Pressure on the Cathode Spot.—For overhead welding a new and unique theory proposes that the pressure of the anode spot on the molten globule of metal at the tip of the electrode depresses the liquid at this point. This depression causes the arc to shift to the high point and in turn depresses this in the same manner. In this way undulations or waves are produced in the molten metal which finally splashes high enough to short circuit the arc after which surface tension acts to attract metal into the pool. Most d.c.

welding in the vertical and overhead positions is done with reversed polarity electrodes in which case the cathode spot is on the work and the theory does not explain the transfer of the metal. Tests on pure iron electrodes, which had been treated so as to be very free from gas, show that it was impossible to weld overhead even on straight polarity. Obviously if the pressure on the cathode spot were responsible for the metal transfer, it should have been possible to weld overhead with the pure iron electrodes.

Expansion of Gases in the Metal at the Tip of the Electrode.—The expansion of gases in the metal at the tip of the electrode is believed to be a primary force in the transfer of the metal across the arc.

When these gases and vapors are liberated rapidly they may occasionally shoot small particles from the tip of the electrode. However, a more likely explanation is that they are formed below the surface of the molten metal and because of the surface tension of the liquid, the expansion of the gases forms bubbles of metal on the tip of the wire. The bubbles may be large or small depending upon whether the gas evolution is general or localized. They may burst due to gas pressure alone, or they may expand until they touch the plate and short circuit the arc. When the bubbles burst they produce a spray of fine particles and when they short circuit the arc they are literally exploded into fine particles by the high current passing through the thin film. A similar action can be readily demonstrated by collecting the particles resulting from short circuiting a small wire across a high current. The described phenomena may be attributed to the impurities contained in the rimmed steel core wire and appears to be the reason for the unsuitability of "killed steel" for core wire.

The rate of heating and gas formation is probably an important factor in the type of bubble formed. Hence, coated electrodes should develop thin walled bubbles due to rapid heating and bare electrodes with low rate of heating should develop thicker walled bubbles. From visual observation or motion pictures it is not possible to distinguish a bubble from a solid drop but the rapidity with which the bubbles or drops form and disappear in the arc of a coated electrode is strong evidence that they must be bubbles and not solid drops. In comparing the oscillograms of bare and coated electrodes several investigators have pointed out that the short circuits on coated electrodes were not only less frequent but also of shorter duration. The short duration suggests that the short circuits are due to bubbles which explode, rather than solid drops, and the infrequency of the short circuits shows that many of the bubbles burst without touching the work.

Arc Crater and Penetration

The base metal terminal is similar to the electrode terminal in that liquefaction and volatilization are localized and there is a sharp temperature gradient. This heat localization produces a depressed area or "crater," the size and depth of which are dependent on temperature, oxidization, surface tension and other factors affecting fusion. See Fig. 2. "Crater depth" *during welding* is a definite indication of the depth of fusion or "penetration" being obtained—Figs. 2 and 3. However, the depth of a crater *in a completed weld* is not necessarily indicative of this feature, as craters of properly shielded processes are relatively shallow, Fig. 2*A*, and

the crater may have been intentionally filled when the arc was broken. Weld craters are caused by:

(*a*) The pressures of the expanding gases and of the electron stream from the electrode tip, both of which blow the liquid metal toward the edges of the crater.

(*b*) The higher temperature of the center of the crater, and thus a lower surface tension, in comparison with the lower temperature and higher surface tension of its sides and lower adjacent metal.

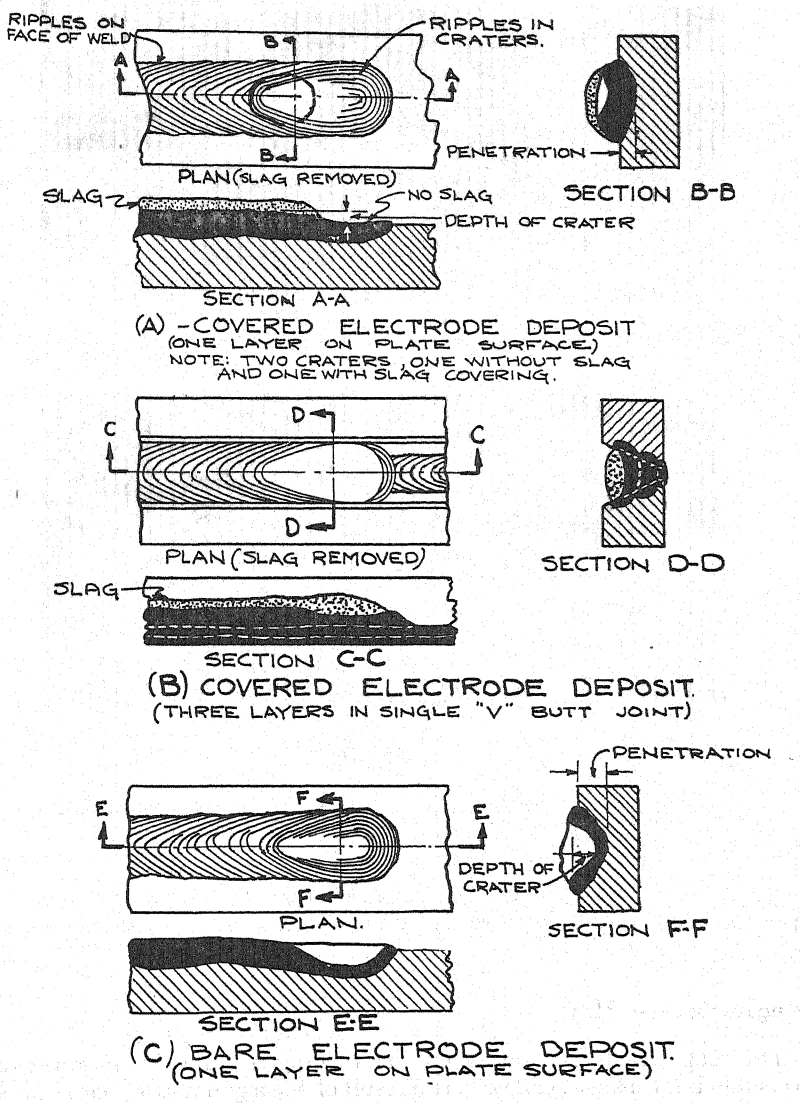
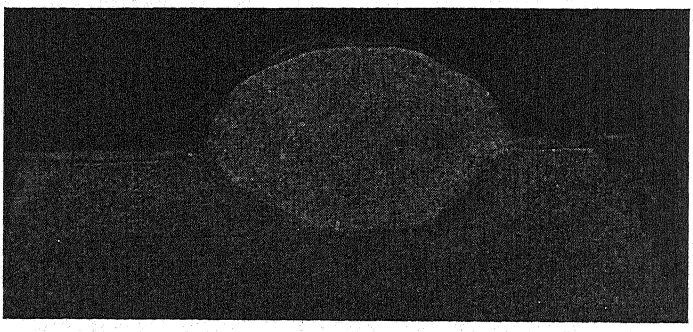


Fig. 2—Typical Shielded and Unshielded Metal Arc Craters

These differences in surface tension upset the equilibrium of the crater metal causing concentric waves which freeze on reaching the colder edges or rim. This phenomenon can be observed during welding and all completed welds have rippled faces as shown in Fig. 2. The contour of the ripples is determined by angularity of electrode and speed of welding. The ripples produced by automatic arc welds made at appreciable speeds have the appearance of the waves in the wake of a ship. Furthermore, as the angularity of the electrode in automatic arc welding is usually the



(A) Covered electrode deposit.



(B) Deposit made with bare electrode or some "all position" shielded arc electrodes.

Fig. 3—Typical Penetration Obtainable for Covered and Bare Electrodes. One Layer (Bead Deposition)

same at all speeds, it is possible for an experienced observer to judge the approximate speeds of such welds by the relative angular acuteness of their rippled surface contours.

Magnetic Arc Blow

The magnetic forces acting on the welding arc and causing the phenomenon known as "arc blow" are a result of the asymmetric magnetic field induced by, and surrounding the path of, the welding current. The dis-

tortion of this magnetic field is caused by three factors, two of which are common to both d.c. and a.c. welding. These factors are:

1. Asymmetric position of magnetic material about the arc.
2. Change in direction of the welding current at the arc terminal.
3. Eddy currents.

1. Asymmetric Position of Magnetic Material About the Arc.—The resultant force on the arc acts toward the best magnetic path, or the nearer of two good magnetic paths, and is independent of the electrode polarity. The position of the best magnetic path with respect to the arc will change as welding progresses, consequently the intensity and direction of the force will change. Causes for the change of the best magnetic path are:

(*a*) A change in the position of the arc and electrode with respect to the work as welding progresses along the joint.

(*b*) The amount of weld metal deposited and the size of the air gap produced by the root or joint opening.

(*c*) The presence of metal in the vicinity of the arc heated above the temperature at which it becomes non-magnetic (about 1350°F.).

2. The Change in Direction of the Welding Current as it enters the work and is conducted away at approximately right angles to the electrode. The current will take the easiest path but not always the most direct path through the work to the ground connection. The resultant force is opposite in direction to the current path away from the arc and is independent of the polarity. In determining the location of the ground connection care must be exercised in determining the actual path of the current through the work to the ground.

3. The Eddy Currents Induced by Alternating Currents in the work tend to neutralize, and therefore decrease but not eliminate, the arc forces produced by the previously mentioned causes. Eddy currents will only be a factor when welding with alternating current and rectified alternating current.

The induced eddy currents cannot occupy the same path as the arc current, and are generally not on diametrically opposite sides of the arc, consequently the fields of the arc current and eddy currents are neither concentric nor in line and a repulsive force on the arc is produced. The eddy currents generally tend to distribute themselves centrally about the nonmagnetic region of the heated metal behind the arc. The resultant force on the arc acts in the direction of welding under closed seam conditions. When welding on an open seam, between two good magnetic paths across the seam, the force is toward the nearer path.

The greatest force on the arc is caused by the difference in the reluctance of the magnetic path around the arc. The location of the ground is of secondary importance but may have an appreciable effect in reducing the total force on the arc. The total force on the arc may be reversed by changing the ground location only under the less severe conditions when the reluctance of the magnetic path about the arc is fairly symmetrical.

A measurable force acts on the arc when welding with alternating current but it is generally reduced to an easily handled value.

The magnetic forces acting on the arc may also be modified by changing

the magnetic paths across the joint with steel strips, starting plates, tack welds, the welding sequence used, etc.

The use of an external field produced by a permanent magnet, an electromagnet or a combination of both will also be effective. An external field of this type is not effective when welding with alternating current unless the field is produced by an a.c. source of the same frequency and with the proper phase relationship to the welding current.

The conditions which affect the forces acting on the arc vary so widely that it is impossible to make general recommendations for reducing or controlling these forces. A.c. power has been demonstrated to be a most effective method of reducing magnetic arc blow, however.

Circuit Characteristics and Arc Stability

Regardless of the method of attainment, a highly reactive circuit is essential for metal arc-welding processes if current surges are to be kept within reasonable limits and to insure instantaneous voltage recovery from short circuiting values of 3 volts to normal arc voltages of 11 to 40, depending on the process.

Experience has shown that current surges due to short circuiting of the arc, and as indicated by the static volt-ampere characteristic curve, should not exceed the welding current by more than 100% and not less than 10%. Furthermore, tests clearly indicate the importance of instantaneous voltage recovery as a factor in securing arc stability under all welding conditions.

Sound welds cannot be produced with an unstable arc due to the liability of intermittent fusion, the trapping of slag and the production of blow-holes.

To relieve the current source of heavy fluctuations, the trend is to design electrodes capable of being consumed by the arc at a practically constant power input. This is attainable with heavily covered electrodes of large current capacity. However, as the use of large electrodes is restricted to flat welding, welds of appropriate form and joints of appropriate thermal capacity, it becomes necessary to rely on suitably designed equipment to obtain arc circuits which respond instantaneously and without surges to the rapid voltage fluctuations characterizing:

(*a*) The use of the smaller sizes of electrodes and the lower currents which are required for the welding of many products, and—

(*b*) The use of these sizes of electrodes and current values for welding in the horizontal, vertical and overhead positions.

Effect of Filler Metal Compositions and Heat Treatment of the Wire on Arc Stability and the Physical Properties of the Weld Metal

Impurities in the weld can be traced to one or more of the following factors—the filler metal wire, the filler metal coating or covering, imperfect shielding, dirty joint surfaces and the base metal welded.

In bare and covered electrodes, the chemical composition of the filler metal wire plays an important role in arc stability and affects the physical

properties of the weld metal. In uncoated bare electrodes, the composition of the wire is a major factor in determining arc stability. However, arc stability may be greatly improved by the coating on lightly coated electrodes. To illustrate the extreme sensitiveness of the arc to the condition of the electrode surface, it has been found that an argon shielded arc will be erratic unless the electrode has at least a sull coating.*

Both arc stability and weld properties can be decidedly influenced by the nature of the covering materials used on covered electrodes. The detrimental characteristics of the wire cores of both lightly coated and of covered electrodes cannot be wholly overcome or eliminated by the influence of the materials used in their coatings or coverings. Impurities in large volumes and forming close conglomerations are particularly harmful.

While it is of lesser importance, it is essential that the wire core shall be of normalized grain structure as the specific electrical resistance of mild steel in this condition is most suitable for the purposes of arc welding. Lack of uniformity of the final heat treatment of the wire core is often responsible for the erratic behavior of electrodes covered with a matrix obtained from the same batch and processed under identical conditions.

Phosphorus and sulphur are transmitted through the arc practically without loss. Sulphur is harmful when in excess of 0.04 per cent, although 0.05 per cent is permissible in the higher alloys. Sulphur acts as a slag, breaks up the continuity of the weld metal and produces "hot shortness." It is particularly harmful when the manganese content is low as in bare low carbon steel electrodes.

Silicon can be satisfactorily introduced into the weld in processes wherein the filler metal is independently melted in the arc. In metal arc processes, silicon tends to produce an unstable arc in quantities of less than 0.1%, whereas manganese aids in arc stabilization and weld soundness. In order to assure that the weld metal, in solidifying, fully vents its gases, it is essential that the carbon-manganese balance of core wires shall be that which is capable of satisfying the temperature conditions of the arc. The temperature reached and the time that the weld metal remains molten are partly a function of the composition and volume of the covering. The most suitable compositions of core wire and coatings are interrelated.

Arc stability is materially affected by the presence in the electrode wire or on the electrode surface of certain substances either in the form of pure elements or their oxides. FeO (Fe_3O_4, Fe_2O_3), CaO($CaCO_3$), TiO_2, MnO, FeS, etc., tend to stabilize the arc. Al_2O_3 (Al), SiO_2, (Si), $FeSO_4$ decrease stabilization. Al and Al_2O_3 are the most effective nonstabilizers, causing arc instability when present in small quantities.

The coatings used on light coated electrodes provide an ionized path for the current and increase the fluidity of the molten metal. These materials are chiefly TiO_2 and several oxides of iron. The coverings used on covered electrodes shield the molten metal in its passage through the arc, and during solidification by liberating organic or inorganic inert gases. The molten metal is further protected and its cooling rate slowed

* The light coating left on the wire of iron oxide obtained by a process of rusting after pickling in sulphuric acid.

down by a layer of slag which originally formed a part of the covering. The organic materials used as gas generators are burned sugar, cellulose in several forms, gums and starches. The inorganic gas generators are usually low melting point spars. The slag forming materials are alumina and silica. The arc stabilizing materials are those given above.

Blow-Holes and Slag Inclusions in Weld Metal

The occurrence of blow-holes in weld metal deposited by arc welding may be attributed to a variety of phenomena, some of which are chemical, others physical, and some may develop as the result of the combination of both sources. The analysis of the phenomena responsible for the development of blow-holes is too complex for the purposes of this text (Fig. 4).

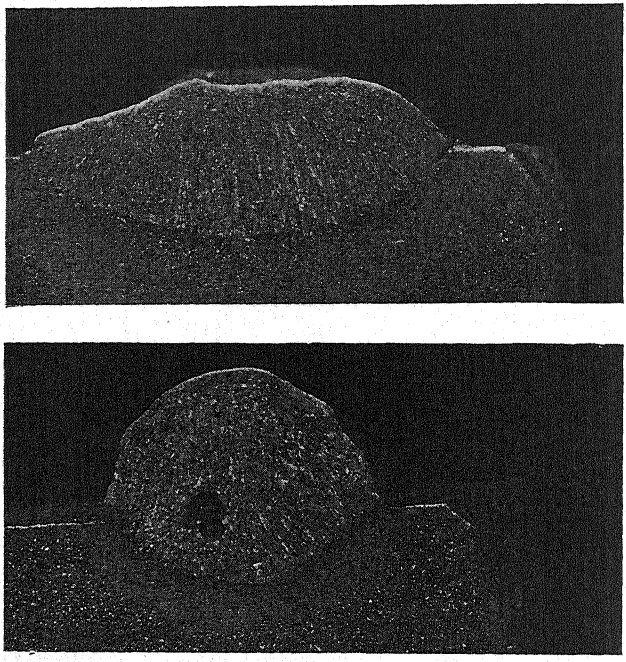


Fig. 4—Typical Blow-Holes and Slag Inclusions

Blow-holes occur in weld metal deposited from mild and medium alloy steel-covered electrodes under the following circumstances:

(*a*) Covering too dry (Chemical).
(*b*) Covering too moist (Chemical).
(*c*) Improper slag reaction (Chemical or Ceramics).
(*d*) Poor joint design (Physical).
(*e*) Base metal analysis (Chemical).
(*f*) Filler metal analysis (Chemical).
(*g*) Poor welding technique (Physical).

Certain types of non-ferrous electrodes can be deposited in properly designed joints consistently free of blow-hole formations owing to the pres-

ence of a scavenger element which is alloyed with the core wire and which appears in the weld metal only in negligible quantities.

Increase of moisture content in other non-ferrous electrodes, particularly of aluminum and aluminum alloys results in excessive porosity in the weld metal.

Slag inclusions in the weld metal deposited from well-designed covered electrodes may be attributed almost exclusively to poor joint design, arc blow, or improper manipulation of the electrode or to the combination of these two causes.

Effect of Base Metal Compositions and Properties on Arc Stability and Weld Properties

Sulphur is limited in the usual specifications for base metal. Its presence in quantities larger than these specified amounts generally indicates steel of poor welding quality. Carbon, and to a lesser degree, some of the alloying elements used in the manufacture of steel can be not only a source

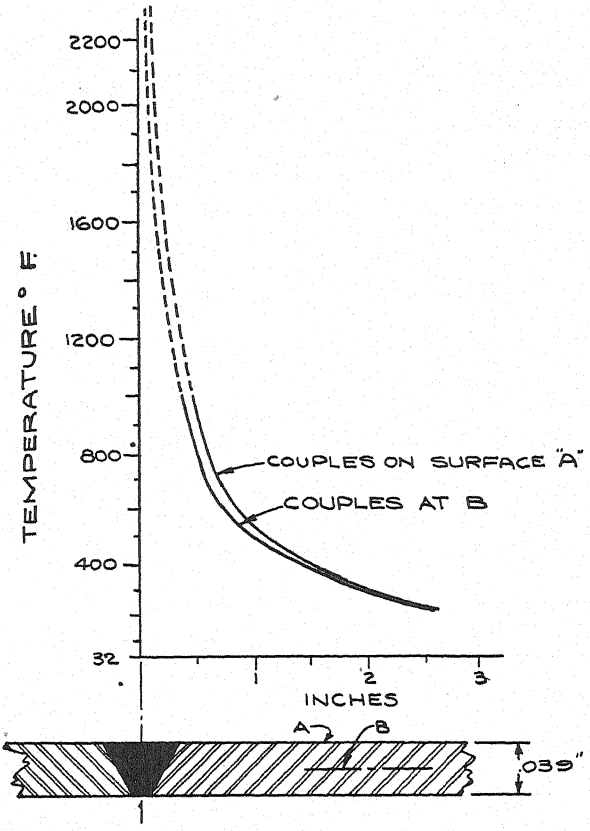


Fig. 5—Typical Heat Gradient for Covered Electrode Welds in Carbon Steel Plates

of trouble from blow-holes and poor penetration, but a source of danger from small stress cracks in the fusion zone due to their hardenability when quenched by the sharp temperature gradient between the molten base and weld metals and the adjacent unmelted base metal. See Fig. 5. This danger is overcome by limiting the carbon content in carbon steel for arc welding to 0.35% and in alloy steels from 0.07 to 0.25% depending on the compositions used. The A.W.S. Bridge Specifications limit the carbon content to 0.25%, and some authorities recommend a maximum of 0.15% for low alloy steels.

Cracking can be overcome in weldable high carbon and alloy steels by a reduction in the temperature gradient by means of preheating, thus reducing quenching action and hardening. Post heating is also, at times, essential.

An increase in current values with a constant speed of travel tends to reduce hardness in the fusion zone, while an increase in the speed of travel with a constant current value tends to increase the hardness.

Open Roots vs. Closed Roots

Open roots, or spaces between the edges of the members to be welded, are used to insure complete root penetration in square, bevel and V butt welds, and to secure attachment to a backing member. J and U joints are often assembled with a closed root in order to obtain better control of the shrinkage. The weld metal of the first pass deposited into the closed root assembly is usually partly removed by chipping or machining on completion or near completion of the weld and then rewelded from the opposite side.

The higher residual stresses resulting from the resistance of the root faces of the weld to the movement of parts joined by U and J welds can usually be taken care of in weldments, wherein these forms of welds can be used, by peening and more thoroughly by stress relieving.

Angularity of Electrode to Work

The angular position of the electrode to the work may determine to a marked degree the quality of the weld metal, freedom from undercutting and slag inclusions, the ease with which the filler metal is placed in the weld, uniformity of fusion and weld contour as affected by the influence of surface tension and gravity on the molten metal (see Fig. 6). The proper angles for various types of electrodes in various welding positions can usually be obtained from the manufacturer.

Striking, Maintaining and Breaking the Arc

The metal and carbon arcs are struck by touching the work with the electrode and quickly withdrawing it an amount not exceeding that required to maintain it under welding conditions.

When a metal arc is struck, there is a tendency for the electrode to "freeze" or stick to the work due to a sudden rush of current induced by the short circuiting of the machine. This tendency is very pronounced in manual bare electrode welding, and it is desirable, when this process is used, to employ a lateral motion to strike the arc similar to that of striking a match.

With some types of covered electrodes, it is necessary when striking the arc to forcibly remove the projecting covering on the electrode tip by tapping it on the work. In striking a carbon arc, care should be used to avoid striking it in a molten crater as particles of slag may adhere to the electrode and cause an irregularly shaped arc.

After a metal arc has been struck, it is maintained by a uniform continuous movement of the electrode toward the work to progressively compensate for that portion which has been melted and deposited in the weld. At the same time, the electrode is also progressively advanced in the direction of welding. The two motions when combined are similar to taking a pencil in the hand, holding it at 60° to the side of a pad of paper and moving it downward without changing the angle of the pencil. This should be practically demonstrated to students.

Two procedures are used to break the arc. One procedure requires that the arc be shortened and the electrode moved quickly sideways out of the crater. This method is used in manual welding when electrodes are changed and the weld is to be continued from the crater. The other procedure requires that the electrode be held stationary long enough to fill the crater and then gradually withdrawn. It is used in manual and automatic welding when it is desired to minimize or to eliminate the crater.

When the arc is re-established in a crater produced by the former procedure, it should be struck at the forward or cold end of the crater, moved backward over the crater and then forward again to continue the weld. This procedure fills the crater and avoids porosity and the trapping of slag.

Arc Voltage and Length

In arc welding, the arc is a gaseous conductor of electricity. It is not self starting and if extinguished must be re-established. Furthermore, several factors are essential for its continuity, viz.: an ionized gaseous medium, molten slag (if present in the covering of the electrode), a cathode spot and means for feeding the electrode to maintain the required distance between the cathode and anode.

In the arc there are three well-defined voltage zones known as the cathode drop and the anode drop at the terminals, and the arc stream voltage. All three are also thermally defined, as the heat dissipated in each is proportional to the voltage. The cathode and anode gradients remain practically constant and independent of the arc length and current. The voltage across the arc stream proper varies with the arc length but not in exact proportion thereto.

In order to reduce oxidation and porosity to a minimum, it is generally desirable to maintain an arc which is relatively short for the process being used. A long arc is erratic and is also inefficient as it increases the spatter loss—a very short arc is impractical.

It is necessary to maintain a shorter arc for vertical, horizontal and overhead welding than is required for flat welding. The normal arc voltage, in the flat position, for $1/8$-in. to $1/4$-in. bare and lightly coated electrodes is 14 to 25, and for covered electrodes, 22 to 40. The corresponding voltages for the other welding positions are 12 to 22 and 20 to 35, respectively. A 14-volt arc with bare or lightly coated electrodes is approximately $1/8$

in. long, and a 40-volt covered electrode arc is approximately $1/4$ in. long. The length of the arc is also dependent on the type of coating.

Speed of Welding (See Chapter 35)

"Speed of Welding" is a relative term, and is in no sense absolute. Some conception of its relative character can be obtained by a consideration of the following variables involved:

(*a*) Thoroughness of supervisory planning, including advance preparation of procedure controls.

(*b*) Whether the work is pre-assembled or assembled by the operator. If assembled by the operator, the availability of the parts, facilities afforded for assembly and the care with which the parts have been prepared for welding to insure correct root openings, angles of bevels, etc. All of these are important contributing factors in the attainment of speed in production welding.

(*c*) Accessibility of the weld.

(*d*) Thermal capacity of the joint, including backing bars or strips if used. The greater the thermal capacity of the joint, the larger the electrodes and the higher the currents that can be used.

(*e*) Form of weld—fillet, single-V butt, double-V butt, single-J butt, etc.

(*f*) Cross-sectional area of the weld and the care used to insure that weld size, as determined by throat thickness and reinforcements (if any), are within the design limits expected by the designer or imposed by code requirements. The sizes of fillet welds should be measured by suitable weld gages.

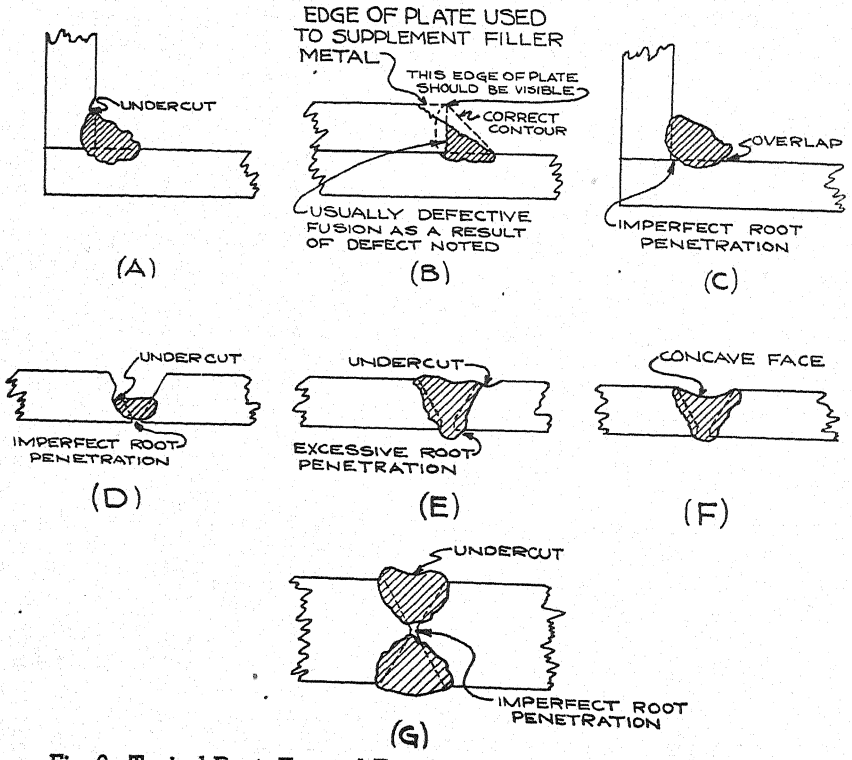


Fig. 6—Typical Root, Toe and Face Defects of Fillet and Butt Welds

(*g*) Continuity of weld—continuous or intermittent.

(*h*) Type of root (open or closed), and whether the root face is melted or chipped out and re-welded.

(*i*) Type and wire sizes of filler metal used to make the weld.

(*j*) Welding processes used (shielded metal arc, unshielded metal arc, etc.), including the type of current (a.c. or d.c.).

(*k*) The value of the current (amperes) employed.

(*l*) Number of beads or layers used to make the weld.

(*m*) Composition of base metal welded and filler metal used.

(*n*) Position of welding—flat, horizontal, vertical or overhead—and whether the weld (if made in the flat position) is "positioned."

(*o*) Fluidity of the weld and base metals.

(*p*) Time required to remove slag, peen, correct defects and change electrodes.

(*q*) Continuity of welding as affected by the use of short length electrodes (as in manual welding), or the use of electrodes in coil form (as in automatic welding).

(*r*) Per cent of spatter and stub-losses.

(*s*) Temperature of the base metal.

(*t*) Soundness of weld metal required.

(*u*) Capacity and design characteristics of the welding machine.

Unless all of the foregoing variables are taken into consideration, it is impossible to definitely state the speed at which any weld may be made, any product can be welded, or to compare the speeds of arc-welding processes, machines or electrodes.

The speed of welding of all processes utilizing filler metal should be stated in terms of pounds of weld metal deposited per hour together with the major variables involved. A survey of all fusion welding processes (manual and automatic) exclusive of Thermit welding, with a proper evaluation of the major variables enumerated, indicates that the speed of welding will vary from $^1/_2$ lb. to more than 100 lb. per hour.

Control of Residual Stresses*

As residual thermal stresses cannot be avoided, and as these stresses may exceed the yield strengths of the base and weld metals, it is sometimes desirable that preheating and/or the stress-relieving methods (thermal or mechanical) given on pages 146 and 147 be used to prevent weld failure. Furthermore, thermal stress relieving is invariably required if the weldment is to be machined and close tolerances are required. On the other hand, *weld failures are unlikely to occur in weldments, which cannot be pre-heated or post-heated, if the following precautions are observed:*

1. In so far as possible, design the product so as to incorporate types of joints having the lowest residual stress—see Figs. 7 to 10. Also avoid highly localized and intersecting weld areas.

2. For joints of high fixity and joints requiring the deposition of multiple layers, specify the use of base and filler metals having an elongation of not less than 20% in 2 in. as determined by 0.505-in. diameter test specimens. Carbon steels having carbon contents less than 0.35% and the weld metal obtained with properly shielded processes comply with this requirement.

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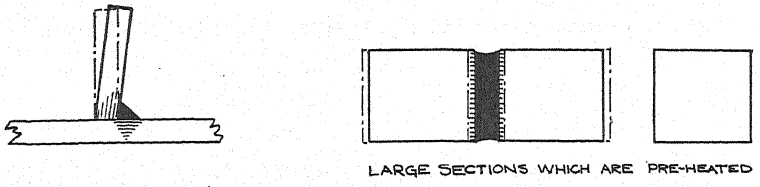
* See Chapter 32B and page 146 for a detailed technical treatment of the subject of Residual Stresses.

3. Specify the peening of all beads and layers (except root and face) of multiple layer welds of appreciable fixity. Beads and layers to be peened should not exceed $^1/_8$ in. in thickness.

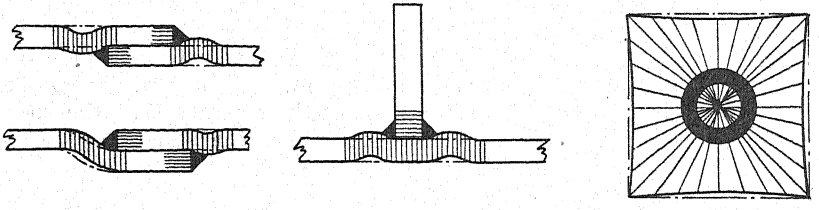
4. Specify the use of assembly and welding sequences which permit movement of the component parts during welding, which do not increase joint fixity, and wherein joints of maximum fixity are welded first. For example, the longitudinal seams of a cylindrical tank should be welded before the circumferential head seams.

5. Specify welding sequences which avoid a unidirectional flow of heat. This is accomplished by use of a "wandering sequence" or by a "step-back sequence." The *wandering sequence* consists essentially in the making of short remote welds and progressively halving the intervening unwelded sections by similar short welds. The *step-back sequence* consists in the making of a short weld at the end or in the center of a seam, and progressing toward the other end or toward both ends of the seam in similar short welds, each weld being started away from the previous short weld.

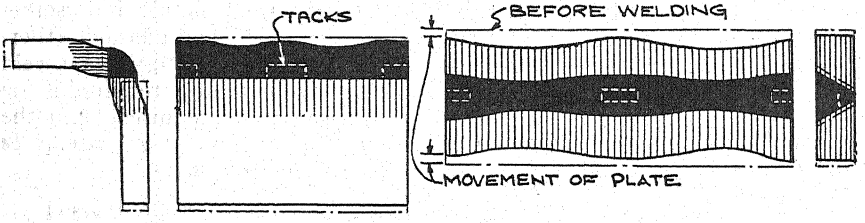
6. Specify welds having shapes, sizes and continuities capable of resisting



(A)- MOVEMENT OF SECTION



(B) - DEFLECTION OF SECTION.



(C)-MOVEMENT AND DEFLECTION OF SECTION

Fig. 7—The Non-Rigid Type of Joint

Residual stress primarily determined by movement of section, deflection of section or movement and deflection of section.

This type of joint is applicable principally to plates and sections as specified. Edges before welding shown by dot and dash lines, after welding by full lines. Area and distribution of residual stress shown shaded.

the service and anticipated residual stresses. In general all butt welds should be continuous and when completed by an appropriate number of layers, should have throats at least equal to the thinner section joined; even if it is necessary to thermally or mechanically remove the root layer and re-weld the root.

7. Specify methods of assembly and sequences of welding which avoid the introduction of bending stresses in the weld.

8. Specify rigid procedure and operator qualification tests, to insure welds which are free from defects and whose physical properties comply with the minimum procedure qualification requirements.

9. Specify that the welds on the ends of members be "boxed" or welded around the end so as to prevent the possibility of a failure of the end welds, and a progressive failure of the joint.

10. Specify that all defective sections of strength welds or cracked tack welds be chipped or melted out before proceeding with the work.

11. On products (for example, ship structures), wherein welding is required in *all positions*, no operator should be employed who has not complied with the required operator qualification tests for *all* positions. Unless this is adhered to, operators will try unobserved, or may even be authorized, to make production welds in positions for which they are not qualified. Another practice which is equally dangerous (unless authorized by a proper authority), is the use of metal slugs in the weld to speed up production or to fill a badly fitted groove. Both of these practices have been known to have serious consequences and should be *absolutely prohibited*, except as noted.

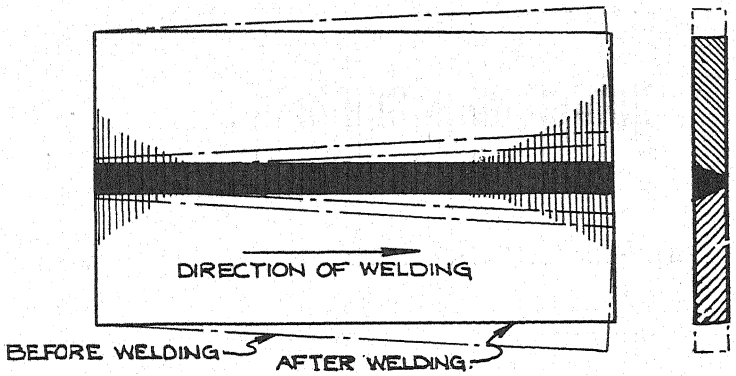


Fig. 8—The Semi-Rigid Type of Joint (Principally Plates)

Residual stress transverse to the joint primarily determined by an angular movement of joint edges in the direction of welding.
Type restricted to butt joints with plate surfaces in the same plane.
Highest residual stress at ends.

Control of Shrinkage

Shrinkage due to welding can be controlled and reduced to a minimum in non-preheated products by the use of:

1. Closed roots.
2. The minimum number of welds.
3. The smallest sizes of welds which will fulfill design, fabricating and service requirements.
4. The minimum number of layers required to satisfy the required weld properties.
5. The maximum use of intermittent welds.

6. Peening. (Except root and face layers.)
7. The use of wandering and step-back sequences.

Due to the number of variables, it is impossible to establish shrinkage values for welds which can be applied to all types of products and materials. The following data can, however, be used as a general guide for unpeened butt and fillet welds in medium carbon steels:

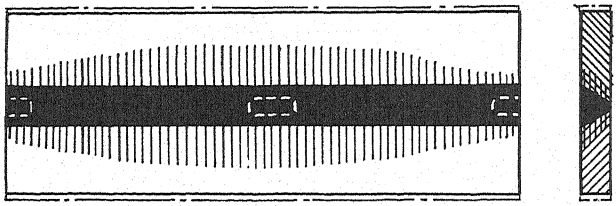
Average Transverse Shrinkage per Joint:

0.025 in.—Two light* continuous fillet welds, or
—One full† continuous fillet weld, or
—One full chain intermittent fillet weld or one staggered full intermittent fillet weld of 50% continuities.

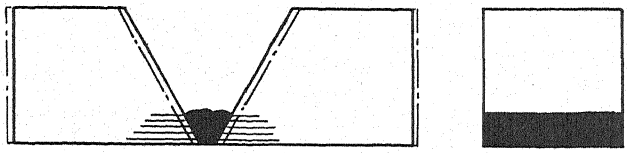
0.07 in.—Two full continuous fillet welds, or
—One 60° single V open root butt weld.

Average Longitudinal Shrinkage per Joint:

0.03% of joint length—Joints having 0.025 in. transverse shrinkage, or
0.1 % of joint length—Joints having 0.07 in. transverse shrinkage.



(A)- PLATE SURFACES IN THE SAME PLANE



(B) – HEAVY SECTIONS IF NOT PRE-HEATED, AS IS USUALLY THE PRACTICE IN ARC WELDING.

Fig. 9—The Rigid Type of Joint (Principally Plates and Sections as Specified)

Residual stress transverse to the joint primarily determined by a parallel movement of joint edges during welding.

Type restricted to butt joints in which plate surfaces are in the same plane, or heavy sections if not preheated, as is usually the practice in arc welding.

Highest residual stress is between ends. Stress is in general alternately tension and compression.

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* A *Light Fillet Weld* is one having legs equal to one-half the thickness of the lighter member joined.
† A *Full Fillet Weld* is one having legs equal to the thickness of the lighter member joined.

Control of Warping

Warping due to welding can be controlled and reduced to a minimum in non-preheated products by:

(*a*) *Pre-springing or Initial Distortion.*—In its simplest application, this method consists of mechanically setting or bending a part in an opposite direction to which warpage is expected so that the effect of welding is to restore the part to its desired shape.

(*b*) *Strong-Backs or Jig Methods.*—The size and variation of ship structures generally preclude the use of jigs of the type frequently applied to small machine or sheet metal assemblies. A variation which is applicable to large structures is the use of strong-backs and temporary stiffening by which the structure is given increased resistance to distortion but which are removed after the welding has been completed and cooled.

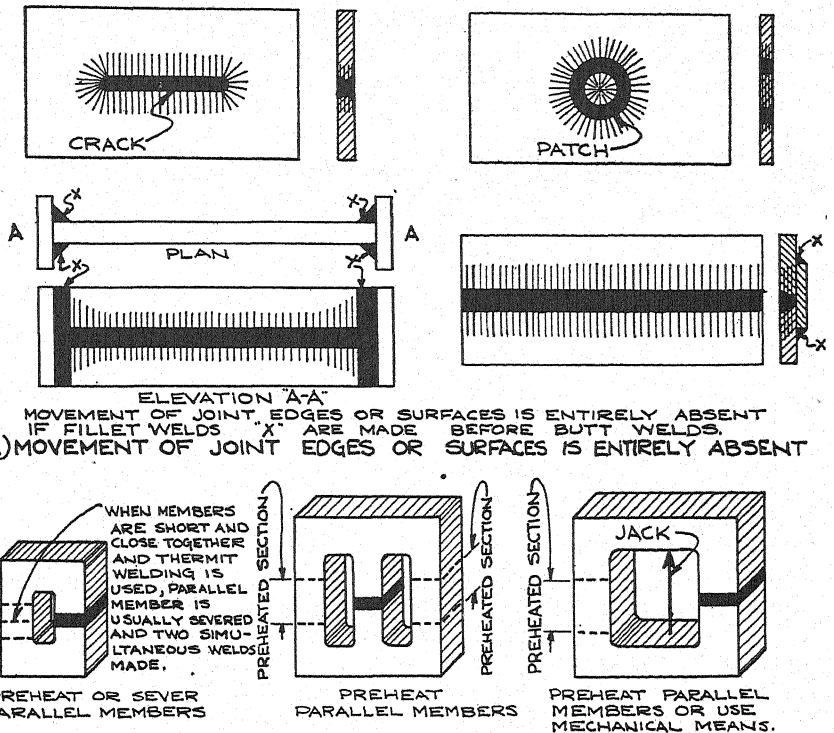


Fig. 10—The Fixed Type of Joint

Residual stress primarily determined by ductility of base and weld metals, form and sequence of welding, and assembly and treatment (mechanical and thermal) of joint. This type of joint has the highest residual stress and its use should in general be avoided.

This type restricted to butt joints in which movement of joint edges or surfaces is entirely absent, or movement of joint edges is only possible by severing or preheating a parallel member or members or by mechanical means.

(*c*) *Drum-Heading.*—This classification refers to a method frequently used on large areas where the boundaries have a large degree of permanent or temporary restraint. The effect of the welding operations on plating tends to shrink it in size and, as a result of the boundary restraint, the plating is kept flat.

(*d*) *Extent of Tacking, also Wandering, and Balanced Welding Sequences.*—These methods are variations of the drum-head or restraint method. If the entire structure, or a considerable section of the structure is heavily tacked and balanced and/or *wandering welding sequences* are employed which involve the virtually simultaneous completion of all welded connections, as opposed to successive completion frame by frame, or section by section, there may be a considerable reduction in distortion due in part to restraint and part to reduction in local heating. In a *balanced welding sequence,* an equal number of welding operators simultaneously weld in areas geometrically disposed on opposite sides of the structure or of a neutral axis, thus introducing balanced stresses in the product or structure.

(*e*) *Design.*—The importance of design in reducing distortion cannot be overemphasized. In this classification falls the use of a minimum amount of filler metal, and suitable arrangement of joints to avoid localized areas of extensive shrinkage.

Corrective measures for warping can be roughly classified as follows:

(*a*) *Shrinkage.*—While varying in detail, this method consists of alternative heating and cooling, frequently accompanied by hammering or mechanical work, thus shrinking excess material in a wrinkle or buckle.

(*b*) *Shrink Welding.*—This is a variation of (*a*) above, in which the heat is supplied by running beads of weld metal on the convex side of a buckled area. On cooling, the combined shrinkage of the heated base metal and the added weld metal removes the distortion. The beads of weld metal may then be ground off if a smooth surface is desired

(*c*) *Added Stiffening.*—This method, which is applicable only to plate panels, consists of pulling the plate into line by strong-backs and welding additional stiffening to the plate to make it retain its plane. In addition to the stiffness added, there is also benefit from shrinkage in the connecting welds.

It is important to note that certain of the preventive measures, notably drum-heading, extensive tacking, and the wandering sequence as well as the corrective methods of thermal shrinking and shrink welding, are directly opposed to the theory that the structure should be free of residual stresses. The success of these measures is due to the fact that opposed and equal stresses are set up. Taken rather broadly, structures tend to relieve themselves of high stress by distortion. It follows that the prevention, and/or correction of warping usually means the introduction of residual stresses in the product.

Stress-Relieving Methods

In addition to preheating, one or more of the following mechanical or thermal treatments may be used to wholly or partially eliminate residual welding stresses.

1. *"Cold peening" of the weld metal* (except root and face layers). A pneumatic chisel with a blunt rounded edge is employed. Effective peening requires considerable judgment. Cracks can be produced by excessive peening. The usual practice is to peen the weld at a temperature cool enough to permit the hand to be placed on it without serious discomfort. However, it has sometimes been found necessary to authorize peening immediately after deposition, and in other cases after the weld has cooled to room temperature. Tests have indicated that it makes no difference which method is used in so far as the final value of residual stress is concerned.

2. *Stressing the base metal beyond the yield point,* by mechanical, hydrostatic or other suitable methods.

3. *Full annealing.*

4. *Stress relieving.*

The first method is extensively used on statically and dynamically loaded products, but on some products subject to dynamic loading thermal stress relieving is also required.

The second method is rarely used because of the problems involved in its practical application. It is effective and has commercial possibilities on simple products. It has been used successfully on large diameter pipe lines.

The third method, which is superior to stress relieving, cannot be indiscriminately used due to the heavy scale produced at the high temperatures required (1600 to 1650°F.), and because some types of products would collapse at this temperature.

The fourth method overcomes the objections to the third method and is extensively used. See Chapter 32B on "Stress Relieving."

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CHAPTER 4B

ARC-WELDING EQUIPMENT*

Power Equipment for Arc Welding, Performance Tests, D.C. Welding Machines, A.C. Welding Machines and Transformers, Meters, Double Carbon Arc Brazing Torch, Welding Leads, Electrode Holders, Safety Accessories.

Classification of Power Equipment for Arc Welding

POWER equipment for use with the various arc-welding processes may be classified into five distinct types as follows:

Type 1—Single operator, variable voltage, d.c. generators, and motor generators.

Type 2—Single or multiple operator, constant voltage, d.c. generators, and motor generators.

Type 3—Single operator, d.c. arc rectifiers.

Type 4—Single operator, variable voltage, a.c. transformers.

Type 5—Single operator, variable voltage, a.c. rotating motor generators, frequency changers, phase changers or combinations thereof.

Current and Voltage Ratings on D.C. Generators.—The following are N.E.M.A. standard current and voltage ratings for motor-generator type variable voltage welding machines.

Normal Ratings, Amp.	Time, Hours	Loaded Voltage†	Current Range	
			Minimum	Maximum
100	1/2-hr.	30	20	125
150	1/2-hr.	30	30	187
200	1/2-hr.	30	40	250
200	1-hr.	40	40	250
300	1-hr.	40	60	375
400	1-hr.	40	80	500
600	1-hr.	40	120	750
800	1-hr.	40	160	1000

† Loaded voltage is the voltage between the welding terminals of the welding unit when current is flowing.

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D.C. power supply may be 115, 230, 550 or 400 to 650 trolley voltage. A.C. supply may be 2 or 3 phase, 25, 50 or 60 cycles and 220, 440 or 550 volts.

On the *constant voltage* machines, the voltage is 60 and 70 volts, with current ratings of 500, 750, 1000, 1500, 2000 or 2500 amperes. Ratings are on a one hour 50°C. rise basis. The a.c. supply voltage may be either 2 or 3 phase, 25, 50 and 60 cycles, 220, 440, 550 or 2200 volts.

Current and Voltage Ratings—A.c. Transformer Type Arc Welders.—The following table gives standard current and voltage ratings for transformer type arc welders:

Normal Rating, Amp.	Duty Cycle for Manual Welding, %	Loaded Voltage	Current Range	
			Minimum	Maximum for 10 Min.†
100	40	30	20	140
150	40	30	50	200
200	40	30	50	270
300	50	40	60	375
500	50	40	100	625
750	*	40	150	900
1000	*	40	200	1200

Duty cycle is the ratio of arc time to total time. In operating or testing to determine the rating, temperature rise and other characteristics, the maximum time during which rated current is applied should not exceed 5 minutes for units with a 40% duty cycle, and 10 minutes for those with 50% duty cycle.

* On these units normal current shall be applied for one hour, followed by the application of 75% normal current (i.e., the continuous rating) for three hours.

† Maximum current at rated load voltage and rated primary voltage (at welder terminals) for a maximum time of 10 minutes without injurious heating.

In the new standards under consideration the open circuit voltage is limited to 80 volts for manual welding and 100 volts for machine welding. The primary supply is single phase a.c. 25, 50 or 60 cycles; 208, 440 and 550 volts.

Variable Voltage Equipment

"Variable Voltage" or "Constant Energy" d.c. and a.c. equipment delivers approximately constant electrical energy within the range of voltage variation in the arc which occurs in manual welding. For example, if the arc voltage of the electrode is normally 37 volts and the machine is set at 260 amperes, then the wattage in the arc is 9620. Suppose, however, that the operator should temporarily hold a 40-volt arc, the current would automatically drop to 9620/40 or 240 amperes, without any change in arc energy. This feature of variable voltage equipment materially aids in preventing the frequent extinction and sputtering of the arc in the hands of inexperienced operators and aids experienced and conscientious operators to make consistently sound welds.

Constant Voltage Equipment

This type of d.c. equipment comprises a generator set which supplies a constant voltage to the welding system which may supply a number of welding operators. The current for each operator is drawn from this system through a suitable adjustable resistance with which the operator controls the amount of current in his arc.

Selection of Power Equipment

Sound welds can be produced with arc-welding equipment which has been built under N.E.M.A. standards. However, selection of type, size and rating should be based on the character of the work contemplated, and never on budgetary considerations. Where the bulk of the work consists of light gage material, with only an occasional demand for the welding of medium weight material, then the purchase of one or more light and one medium capacity machine is desirable. The performance of most welding machines is not uniform throughout their entire range, and if used at or near the extremes of their ranges, their performance is bound to be less satisfactory than if used at approximately 75% of their rated capacity. Another method is to parallel two of the smaller machines for the occasional heavy work.

The source of the primary current should also be given full consideration. Heavily loaded shop lines carrying suddenly imposed loads, such as cranes, accumulators and resistance welding machines, often cause so much voltage fluctuation in the power circuit as to make them undesirable as sources of power for arc-welding equipment. When such is the case, the choice of equipment to be purchased may be influenced by the available source of power.

Multiple operator equipment is advantageous where a number of relatively low current arcs are grouped in a limited area and when operating factor (ratio of arc time to total time) is low. Single operator sets have the advantages of portability and greater independent adjustment and control of arc characteristics. The choice of a.c. and d.c. equipment from the standpoint of arc blow, power factor and other considerations, has also been discussed under "Alternating and Direct Current Processes," Chapter 4A.

Performance Tests for Power Equipment

There are no generally accepted or specified methods of testing the performance of welding machines other than those established by N.E.M.A. covering rating, temperature rise, range of adjustment, etc. The most widely used test, which is based on the measurement of the recovery time and the amount of surge of the current under transient load conditions, is highly controversial and is not generally accepted. It requires special equipment, considerable skill and experience to test for these characteristics and to evaluate the results of the test. Prospective buyers must rely, therefore, on at least two of the following:

(*a*) Assurance that the equipment under consideration has been manufactured by a reliable concern under the N.E.M.A. standards.

(*b*) The verified performance of equipment already in use with processes which are identical or very similar to those contemplated.

(*c*) Practical tests conducted on their premises and under their own supervision.

While the latter method usually entails considerable expense to all of the parties involved, nevertheless it may reveal merits which might not have been appreciated by the prospective buyer or may even serve to refute claims, made in good faith perhaps, but not demonstrable under the conditions chosen as typical for the product, process and operating conditions involved.

Meters

Many of the power equipments for welding are equipped with instruments for current and voltage readings. These should be well-built voltmeters, ammeters or voltammeters. They should be checked when installed, also inspected and the calibration checked at regular intervals not exceeding six months to assure reliable process and operator qualification test data, to facilitate compliance in production with the user's standards, and to assist the inspection of the product during fabrication. They should furnish correct current and voltage readings within the ranges normally required by the user for his processes.

However, on account of the vulnerability of instruments on welding sets, there is a tendency lately to omit meters, and supply means to easily attach a test meter, which may be kept in a safe place when not used.

The setting of the machines for the desired current output is done by the employment of precalibrated dials or indicator plates.

A.C. Welding Machines

Not only variable voltage a.c. welding transformers but also variable voltage a.c. motor generators, frequency changers, phase changers or combinations thereof are used for a.c. metal arc welding. All of these types of a.c. arc-welding machines depend partially upon the resistance and largely upon the reactance of the welding circuit to reduce the secondary voltage from the no-load voltage to that required for welding. This stabilizes the arc by displacing the current and voltage waves so that they do not pass through zero at the same instant.

Low Voltage Arrangement for A.C. Welding

Several methods have been developed for holding the open circuit voltage in A.C. welding to a value approximately equal to the welding voltage, such as:

1. Providing separate low voltage supply, A.C. or D.C., for actuating contactors to bring in the welding current.
2. Separating the transformer into two units which are only placed in series under load.
3. Push button arrangement to disconnect holder when the arc is broken.

Devices are available which operate automatically or manually.

Welding Transformer

To be satisfactory for arc welding in general, the transformer must fulfill a number of requirements including:

(*a*) Sufficiently high open circuit voltage to make the arc easy to strike but not too high to be dangerous.

(*b*) The method of current adjustment should be simple and at the same time provide the necessary gradations needed in the work.

There are two principal methods of controlling the current, viz.: The Reactance method and the Resistance method. In the *reactance method of control*, a movable core or tapped winding or combination is shifted into various positions by turning a hand wheel, whereas, in the *resistance method of control*, a resistance is switched in and out of the welding circuit by means of switches. This latter method is used for low capacity equipment, as the over-all efficiency is considerably reduced. The power factor, however, may be as high as 90%. In the reactance method, the transformer efficiency is high but the power factor is low.

With large capacity transformers, the power factor may be corrected by the installation of capacitors in the circuit. In addition, it is sometimes desirable to make provision for the effect that the single-phase load of the transformer imposes on the power circuit. If more than one transformer is employed, this can be accomplished by distributing the transformers on different phases of a two- or three-phase circuit.

A jump spark type of welding transformer, employing a superimposed voltage of high frequency in the order of 100,000 cycles obtained either by spark gap or tube oscillations, and developed to improve the arc characteristics and makes transformer alternating current welding more suitable for very light work and for the welding of low melting point metals, stainless steel and some non-ferrous alloys such as aluminum and monel. The electrode need not be touched to the work as the high frequency current jumps the air gap and the welding current follows the electronic path thus established. This feature makes it possible to obtain low and accurately controlled currents of $^1/_2$ to 50 amperes and to use bare electrodes. The superimposed high frequency type of transformer has been found advantageous in the double carbon and gas shielded processes.

A modified form of high frequency has also been incorporated in welding transformers and the equipment is known as the *controlled oscillation capacity type*. One form utilizes a multitapped voltage control of a condenser. There is no jump spark effect and contact must be made to start the high frequency electronic path.

The semi-flash type of welding transformer utilizes an arc voltage which is not sufficient to sustain a continuous arc but is sufficient to start a set of successive flashes which deposit some metal at each flash. The electrode used is usually pure nickel or a nickel alloy, although a low carbon steel can be used. This type finds its widest field of usefulness in the repair of defects in cast iron as the short arc duration leaves no hard spots due to the small amount of heat and penetration. It is found useful in repairing defects in cast-iron cylinder bores, valve seats and so forth. Two or three flashes can be obtained practically simultaneously by a skilful operator.

The Motor Generator Type of Welding Machine

A number of satisfactory types of rotating motor generator a.c. welding machines have been developed for the welding of light sheet metal and the heaviest sections. The type most widely used is the frequency converter type in which the arc characteristics are improved by stepping up the frequency to the range that not only gives the best welding characteristics but permits the equipment to be built on a commercial basis. The range of arc frequencies employed for this class of machines is between 180 cycles and 240 cycles.

Two methods are usually employed to obtain the variable voltage high frequency welding arc. One consists of a motor generator set employing a driving motor and a high frequency alternating current generator. This method of generating the high frequency requires the use of a fairly high speed set in order to be economical and the entire power is transmitted through the motor to the generator. The other method of generating the high frequency alternating current arc is by the use of an induction frequency converter consisting of an induction motor and a wound rotor for generating high frequency. This set takes advantage of the transformer action of the induction generator and employs a smaller motor for the same capacity, and does not require the higher speed to obtain the same frequency conversion.

Several methods of control are in use with this type of equipment to provide the gradations of current necessary for welding. One method used with the straight motor high frequency generator set employs a variable reactor. Another method employed with the induction frequency converter type of set uses a step or stepless type of variable reactor in the primary of the generator circuit.

One principal advantage of the rotating type of welding machine is the fact that it does not create an unbalanced load on the polyphase power circuit.

The Double Carbon Arc (Brazing Torch)

Double carbon arc equipment consists of two angularly arranged carbon or graphite electrodes mounted on a holder with provision for moving the electrode terminals to strike or break the arc as required.

This equipment produces a flaming arc similar to that of an arc lamp projector and is used like a gas welding torch, with or without a welding rod. Edge and corner butt welds can be readily made with this equipment; however, its widest use is for soldering and brazing steel and nonferrous materials, and for localized preheating, stress-relieving and annealing operations.

A $^1/_2$-in. plate can be accurately and quickly bent by locally heating it by this method along the proposed bend.

Welding Leads, Electrode Holders, Cable Splices and Ground Clamps

Welding leads should be proportioned to the class of welding service—continuous or intermittent—distance of work from machine, and nature of

current used (a.c. or d.c.) (see Table 1). It is recommended that for more economical operation the cable sizes given in Table 1 be used whenever possible as these sizes will result in only a 4-volt drop in the cables; in other words, the power loss in the cables will then amount to 10% of the output of the machine at 40 volts. Electrode holders should also be properly balanced, and when a large number of operators are employed on a variety of work it is usually desirable to maintain a stock of various sizes and types preferably of the insulated type. At least ten feet of the "electrode holder lead" adjacent to the holder should be the most flexible rubber covered cable obtainable to enable the operator to readily manipulate his electrode. The "ground lead," and remainder of the electrode holder lead, need not be as flexible. Every user should standardize on sizes and lengths of electrode holder and power leads. The lengths and sizes of electrode holder leads in general use are, respectively, 25, 50 and 100 ft., and 2/0, 3/0 and 4/0. Electrode holders, cable splices and ground clamps should be thoroughly fastened to their leads. Furthermore, loose and vibrating ground connections should be avoided as they interfere with the maintenance of a steady arc. The importance of using welding leads of ample carrying capacity cannot be stressed too strongly. A 50-ft. lead of a given size may be ample to carry the required current, but should another 50-ft. length of the same size be added, the combined resistance of the two leads may be such that the welding current is reduced in proportion to the resistance, or if the machine is readjusted for higher output, it places an additional load on the drive motor. This condition tends to lessen the quality and quantity of the work caused by the use of unsuitable current values and by frequent interruptions to reset the machine.

Table 1—Recommended Sizes of Welding Leads (Electrode Holder and Ground)

NOTE: Based on Direct Current and 4-Volt Drop. Use Next Larger Size for A.C. Welding.

AMPS.	DISTANCE IN FEET FROM WELDING MACHINE											
	50	75	100	125	150	175	200	225	250	300	350	400
100	2	2	2	2	1	1/0	1/0	2/0	2/0	3/0	4/0	4/0
150	2	2	1	1/0	2/0	3/0	3/0	4/0	4/0			
200	2	1	1/0	2/0	3/0	4/0	4/0					
250	2	1/0	2/0	3/0	4/0							
300	1	2/0	3/0	4/0								
350	1/0	2/0	4/0									
400	1/0	3/0	4/0									
450	2/0	3/0										
500	2/0	4/0										
550	3/0											
600	3/0											

Safety Accessories

Safety accessories are of five general types, viz.: protection for the eyes, face, respiratory organs, body and neighboring workmen. In arc welding, the most essential protector is a helmet or a face shield in which a removable protective lens and cover glass of rectangular shape are inserted. (See Chapter 31 on Safe Practices in Welding.)

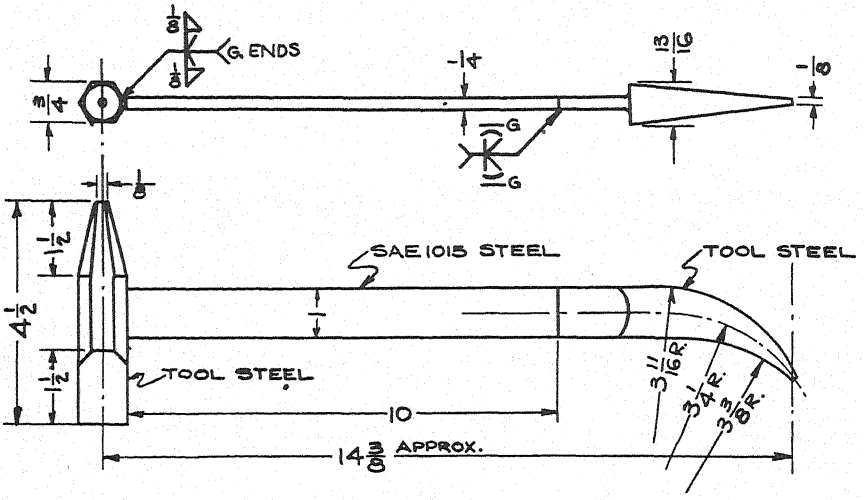


Fig. 1—Standard Slag Hammer

A.C. Safety Devices.—Devices have been developed for manual and automatic reduction of the open circuit voltage on both the transformer and rotating types of equipment.

Welding Operator's Tool Kit

The average operator's personal tool kit should contain his steel identification stamp, fillet weld gages, for $^3/_{16}$-in., $^1/_4$-in., $^5/_{16}$-in. and $^3/_8$-in. welds, a machinist's hammer, an 18-in. spirit level, a plumb bob, a 12-in. combination square, a 6-ft. flexible steel rule, several flat and gouge chisels, a light-weight slag hammer (Fig. 1), a stiff wire brush, a center punch, a scriber and a stick of soapstone.

The employer should provide light-weight pneumatic hammers for slag removal and heavier hammers for peening and chipping; also safety goggles.

CHAPTER 4C

AUTOMATIC ARC WELDING*

Theory of Automatic Welding Equipment, Welding Electrodes, Advantages of Automatic Over Manual Welding, Shielded Arc Welding, Equipment and Manufacturing Data, Special Attachments.

General

IN ORDER to make a successful weld by the metallic arc-welding process it is essential that a practically constant arc length be maintained. This in turn requires that the welding electrode be fed or moved toward the arc at a rate sufficient to compensate for the portion of the electrode that melts away and becomes deposited on the work.

In manual welding the maintenance of a practically constant arc length is the duty of the welding operator and this is accomplished by constantly watching and listening to the sound of the arc. The maintenance of the proper arc length, therefore, becomes a function of the skill and vigilance of the welding operator during the welding operation. As a result, if the proper arc length can be maintained automatically, thereby taking this variable away from the operator, better and more uniform welding may be expected. In addition to producing high quality welds, welding with automatic equipment has many other advantages as will be pointed out later.

For a given electrode and parent metal, the arc voltage is a function of the arc length. As a result, by means of the proper electrical and mechanical arrangement, the speed of a motor, used to feed an electrode into the arc, can be controlled by the voltage across the arc and thereby can be made to maintain a constant arc length.

Theory of Automatic Welding Equipment

An automatic welding head is a device for automatically striking and holding the arc between the electrode and the work to be welded. This is done without manipulation on the part of the welding operator after the starting button has been pushed and the necessary adjustments made.

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The electrode wire is fed toward the arc at the exact rate to maintain the proper arc length.

There are many methods in use for automatically maintaining the arc and feeding the electrode. It is not within the scope of this article to go into the details of the various methods, consequently only the theory on which some of them operate will be discussed. Regardless of the theory of operation, however, the various machines all contain three essential parts: (1) a motor to feed the electrode, (2) some means of control so that it will strike and maintain the proper arc length and (3) a means of conducting the electric current into the electrode.

Figure 1 shows a picture of an automatic head, the driving motor of which is a variable speed d.c. motor. The speed of the motor is controlled so as

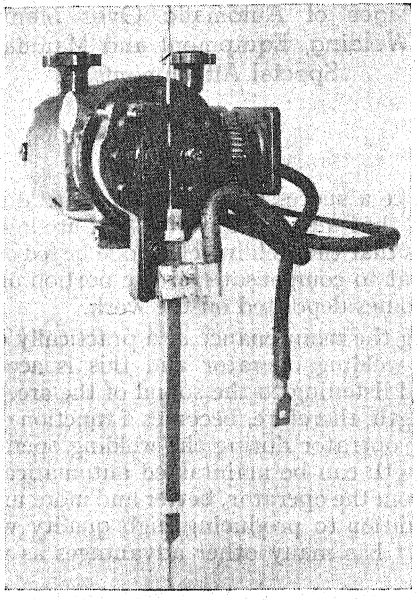


Fig. 1

to strike and maintain the proper arc length by means of a potentiometer type circuit. The armature of the welding head (motor for feeding the electrode) is connected to an auxiliary generator whose field is controlled by the difference in potential between the arc voltage and a reference voltage. If the arc control rheostat is set for a given arc voltage and the electrode is not being fed at the proper rate of speed, thereby causing the arc to become too long or too short, the balance of the system is changed, thereby changing the voltage applied to the generator field. This change causes the auxiliary generator output to increase or decrease which in turn causes the feeding motor to speed up or slow down until the proper arc length is again obtained.

Another type of automatic welding head consists of a single reduction gear wire feeding device with built-in d.c. motor. Full field excitation is

permanently supplied to the motor, and power for the armature is furnished by two Thyratron tubes on the control panel. The tubes are so connected that one supplies current tending to rotate the motor armature in one direction, and current from the second tends to reverse the rotation. The amount and direction of the resulting current supplied to the motor armature depends upon how much the arc voltage is above or below a certain preselected value. The arc voltage is fed to the control through a pair of vacuum tube amplifiers, so arranged that if the plate current in one is increasing due to the arc voltage being above the preselected value, then the plate current in the second is decreasing. The magnitude of these plate currents controls the amount and direction of power passed by the Thyratron tubes furnishing motor armature current, thus the motor speeds up, slows down or reverses, in proportion to the amount the actual arc voltage is above or below the required arc voltage.

Another automatic arc control consists of two electric motors rotating through differential gears, and the resultant motion at the feed rolls is a direct function of the arc voltage and accordingly the difference in speed of the two motors. One motor is a specially wound d.c. motor, rotating so as to feed wire into the work, and its armature is connected across the arc in series with an adjustable arc control rheostat, so that its speed is a direct function of the arc voltage. The other motor is a constant speed a.c. motor, rotating so as to back the wire up from the work.

The differential gearing is such that approximately 300 rpm. difference in speed of the two motors will give the average feed to the electrode. Should it be necessary, because of variations in the arc, to reduce the feed of the electrode, it is only necessary for the down motor to reduce in speed. Reducing the speed of the d.c. motor until it corresponds to the speed of the a.c. motor stops the wire feed. A further reduction in speed withdraws the wire from the work.

Another method of control for automatic welding consists of using small air turbines. These air turbines drive the welding wire feed rolls through a suitable reduction gear. One turbine feeds the wire toward the work and the other turbine feeds the wire away from the work. The air nozzle which directs a blast of air onto the turbines and causes them to rotate is controlled by means of a voltage regulator.

In order to feed the welding wire into the arc, the air nozzle is directed onto the proper turbine. If the arc length becomes too short, the voltage regulator operates and directs the air nozzle onto the other turbine which causes the direction of feed to be reversed, thereby causing the arc to become lengthened to the desired value again. This method of control is entirely mechanical except for the voltage control relay and is capable of striking the arc and maintaining it at any predetermined length.

It should be understood that the methods of automatic arc control described above are by no means the only methods used. They are, however, some of the more common types and are discussed merely to illustrate the many ways equipment can be designed.

Welding Electrodes

Welding current is generally introduced to the electrode by means of a copper alloy nozzle through which the electrode is driven by the automatic

head. This method makes possible the use of coils instead of short cut lengths.

The majority of automatic welding is done with lightly coated electrodes. These are dust-coated, dipped, washed, sul-coated, or bright-finished electrodes, all of which produce welds of moderate tensile strength and low ductility.

The method generally employed of introducing current cannot be applied to heavily coated electrodes due to the insulating nature of their coatings; consequently, if shielded arc quality is desired, special methods must be used. (These methods will be discussed later.)

For welding ordinary low to medium carbon steels, low carbon welding electrodes are used. High carbon electrodes are available for special applications. Electrodes are available in diameters ranging from $^3/_{32}$ in. to $^3/_8$ in., and coils up to 200 lb. in weight.

The light coatings are applied to some types of automatic electrodes in order to stabilize the arc and control the melting rate. High melting rate electrodes generally have low penetration and are therefore suited to light gage materials. When deep penetration is desired, electrodes having moderate melting rate are generally preferred.

Some types of automatic electrodes are knurled or have longitudinal grooves for the purpose of holding more flux coating than can be maintained on a smooth finish. Electrodes of knurled types also have the advantage of a scouring action which reduces or prevents accumulation of coating particles in the nozzle which might cause poor electrical contact.

Advantages of Automatic Welding Over Manual Welding

The advantages of automatic welding are numerous.

1. An operator of limited experience can handle the welding machine and produce satisfactory results.
2. No welding wire is lost in stub ends.
3. A more steady and uniform arc can be maintained.
4. Better fusion is possible because a much higher current can be used for a given diameter of welding wire.
5. A much higher rate of welding speed can be obtained.
6. Welding is continuous from beginning to end of a seam and intermediate craters—which are difficult to avoid where manual welding is employed—are thereby eliminated. The elimination of craters tends to make a stronger, more homogeneous and better weld for retaining liquids or gases under pressure.

The success of any metallic arc-welding operation is dependent upon the maintenance of a uniform arc of the proper length. This requires a great amount of skill and experience on the part of the welding operator. Also even with the best operators it has been found that their ability to hold a steady arc depends to a certain extent upon their physical condition and degree of fatigue. Automatic welding equipments remove this variable and make possible the maintenance of a steady, uniform arc even with an inexperienced welding operator.

The elimination of craters and stub electrode ends are closely related. The advantages of this feature are obvious, however, because it reduces the electrode cost, eliminates the possibilities of poor fusion and inclusions at stops and starts and speeds up the welding. The increase in welding speed

by eliminating the time lost by the operator changing electrodes is in itself a considerable factor in reducing the over all cost of a welded seam.

When welding with any electrode, it is important that it does not heat excessively. In other words, if an electrode becomes red hot, it will function poorly, the arc will become wild and it is impossible to produce sound welds and good fusion. The heating of the electrode is partly caused by its electrical resistance to the current passing through it. This heating may be controlled in two ways: by adjustment of the welding current and by controlling the length of the electrode extending between the electrode holder and the arc.

The welding operator in manual welding with bare electrodes automatically compensates for electrode heating by gripping the electrode in the center and welding from both ends. If welding was done by gripping the electrode at one end, it would be necessary to use a somewhat lower welding current. The manufacturer of coated electrodes sometimes corrects this condition by baring the electrode at the center or by making small diameter electrodes in short lengths. Stainless steel electrodes of $^{5}/_{64}$ and $^{3}/_{32}$ in. diameters are typical examples.

The current-conducting means employed with automatic welding machines makes it possible to conduct the current into the electrode at a point only several inches from the arc. In this way, heating as a result of the electrical resistance of the electrode is held to a minimum and much higher welding currents can be used than is the case in manual welding. This, of course, means higher welding speeds, better penetration and sounder welds.

The automatic control of the arc also makes possible the use of larger diameter welding electrodes without adversely affecting the weld quality. This in turn tends to increase the welding speeds.

Shielded Arc Welding

The major portion of all automatic metallic arc welding is done with bare or light coated types of electrodes because of the ease with which current can be conducted into the electrode. The application of a flux to the electrode in order to produce high-quality welds complicates the problem because this flux is an insulator. Therefore, if shielded arc welding is to be done automatically, special attachments and specially designed electrodes must be used. There are many methods of this type available and there are many thousand feet of automatic shielded arc welds made every day.

One device which permits the use of shielded arc electrodes on automatic equipment is a stick electrode feeding device. As marketed by one manufacturer, this unit consists of an attachment, designed for use with an automatic arc-welding head, which holds a standard 14- or 18-in. length of heavily covered electrode, feeds it into the arc, and automatically stops, ejects the stub end and returns to the starting position ready for welding, as soon as one electrode has been consumed.

This device, in its proper application, combines the advantages of automatic arc welding with those of shielded arc welding, and permits the use of standard types and sizes of electrode. This is a decided economic advantage over processes requiring the use of special electrodes. In addition, it broadens the range of electrode characteristics available for shielded arc automatic welding.

Since the arc must be extinguished at the end of each electrode, a crater is left in the bead, and this factor has been a deterrent to the use of the short length stick feeder on long seams. Its best field of application lies in circular and other short seams, in which one complete pass can be made with one length of electrode. Considerable latitude in the choice of electrode as to length and diameter makes it possible to proportion the weight of steel in an electrode to the amount required by one pass fairly closely, so that excessive stub end loss is not encountered. Owing to the present differential between the price of special shielded arc electrode wire which can be coiled and the price of short lengths as used in manual welding, stub end loss is not a deciding factor in most applications.

Another method consists of putting lugs or projections on the electrode which protrude through to the outer surface of the coating. The current may be conducted into electrodes of this type by means of slide contacts which touch the electrode projections. This type of electrode, therefore, is easily used on an automatic machine.

Although the use of projections through the coating makes current conduction simple, it does not necessarily solve the problem completely. In most cases the flux coating on an electrode is too brittle to coil the electrode. As a result, the electrode must be supplied in straight lengths. If the welding is to be continuous, therefore, it is necessary to join the succeeding lengths of electrodes together by screwing, welding, socketing or clamping one onto the other. This limitation has been overcome in some cases by coiling the wire on large diameter reels.

A third method consists of a special adapter which bares small sections of the electrode at equally spaced intervals and conducts current through these bared sections by means of a series of contacts mounted on an endless chain. This adapter fits onto the welding head proper and the process uses electrodes in wire form.

A practical means of securing uninterrupted automatic arc welds of shielded arc quality is available in an automatic arc-welding head equipped with rubber-tired feed rolls and special current-conducting mechanism for feeding heavily covered or shielded-arc electrodes from a continuous reel or coil.

This process has its widest application in those instances where the highest possible quality, multi-pass arc welding is required. Such applications include deep groove welds in boiler drums, cracking stills, autoclaves and other pressure vessels, in addition to flat and normal position fillets. Both longitudinal and circumferential welds are easily made with this process, the latter including diameters as small as 6 or 8 in.

Essentially, this equipment consists of a Thyratron-controlled automatic arc-welding head equipped with rubber-tired feed rolls, a slitting saw which makes a narrow longitudinal cut through the flux coating of the electrode, and a set of current conducting contact fingers which carry the welding current into the electrode core in close proximity to the arc. The general appearance of this unit is shown in Fig. 2, in which the slitting saw cover is open to show the motor-driven cutter. These units may also be equipped with oscillating devices, with which oscillations up to $1^1/_2$ in. in width may be secured at a uniform, adjustable rate of speed.

Another practical means of securing uninterrupted automatic arc welds

of shielded-arc quality consists of automatically coating the welding wire with a flux tape. Attached to the bottom of the welding head is a box-enclosed mechanism through which the wire is fed after it leaves the welding head. The wire is drawn through two rolls and passed through contact brushes. As the coating has not yet been applied, the wire is not insulated at that point and a positive contact between the brushes and wire is effected.

The wire coating consists of a flux-impregnated tape fed from a reel and wrapped around the wire longitudinally by a series of rolls. This tape coating is applied below the contact brushes and directly above the arc.

An electrode containing an outer mesh of fine gage woven steel wire has also been developed for automatic shielded arc welding. The flux is applied on the outer surface of the electrode between the woven wire mesh and is proportioned so that it does not cover it. This electrode can be

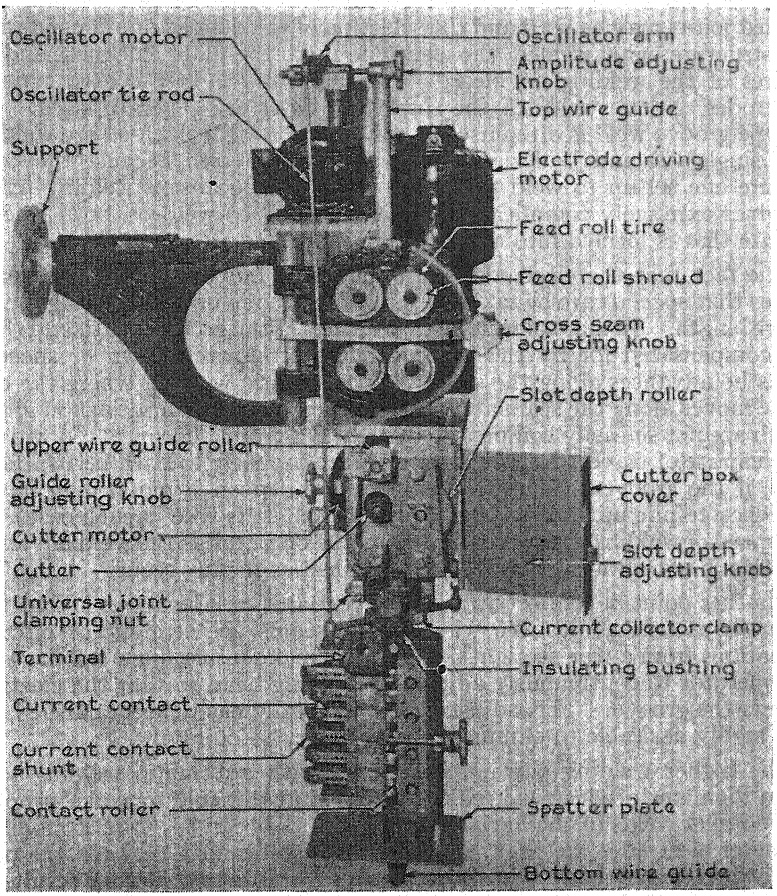


Fig. 2

readily coiled because of the flexibility produced by the wire mesh and current can be conducted into it by simple sliding contacts. It is a truly shielded-arc automatic welding wire and its use should incorporate all the advantages of automatic welding.

Gas shielding around the arc has been tried in many cases, but as yet the results obtained are not as satisfactory as desired. Satisfactory welds have been made, however, on stainless steels by using helium and on certain other materials by using hydrogen.

An extensively used method of automatically producing shielded electric welds consists of applying powdered flux to the weld and using high welding currents. This process is covered in detail in Chapter 7, Submerged Melt Welding.

Equipment and Manufacturing Data

(*A*) *Joint Preparation.*—All the common types of groove and fillet welded joints may be used and the selection of the desired one depends upon the structure being welded, the electrode used, the plate thickness and the desires of the welding engineer. With bare and lightly coated types of electrodes, groove welds of the single vee types are generally used. The U-type groove weld is often used in combination with shielded arc welding. The single vee and U designs are generally preferred because they only require one set-up to weld the entire joint and because a welding fixture becomes extremely complicated if it is designed to weld on both sides of a plate that is formed into a special shape such as a tank shell.

The fact that the electrode is automatically moved along the seam requires that special care be taken to make the groove uniform throughout its entire length. In manual welding, variations in the groove width and shape are compensated for by the welding operator slowing down or speeding up as he advances along the seam. In automatic welding where the electrode moves along the seam at a uniform rate of speed, variations in groove width are not so easily compensated for. If a groove becomes too wide for a given rate of travel, the weld may not fuse properly to both kerf surfaces. Also, if the groove becomes too narrow, the deposited metal may have a tendency to pile up and run ahead of the arc. It is true in such cases that the speed of welding can be controlled by the operator as the weld advances, but this is not always as easily accomplished as it may seem.

Another point in connection with the preparation of grooves is that they be made as true as possible whether the seams are straight or circular. Variations from a true straight line or circle make it necessary for the welding operator to continuously adjust the welding head so that the electrode follows the groove. This adjustment is generally easily accomplished, but it is highly desirable to eliminate the necessity of doing it.

The higher welding currents employed with automatic welding for a given diameter of electrode make it somewhat difficult to make properly shaped fillet welds in the horizontal position. It can be done if moderate diameter electrodes are used, a good fit-up is obtained between the parts and a weld larger than $^1/_4$ in. is not desired. More satisfactory results are obtained by making fillet welds in the flat position by arranging the work at 45° with the horizontal. This procedure allows the use of larger di-

ameter electrodes, higher welding speeds and the production of welds 3/8 in. and over in a single pass.

(*B*) *Auxiliary Equipment.*—Automatic welding in the strict sense of the word consists of more than automatically controlling the arc length and feeding the electrode into the arc. It also consists of automatically passing the electrode along the seam so as to deposit a bead or layer of weld metal. This latter operation is accomplished by the use of special machinery designed to move the work past the electrode or to move the electrode and welding head past the work.

The type of application and set-up determines whether to motivate the electrode or the work. The work is usually moved for:

1. Circumferential seams (both inner and outer) of tanks and pressure vessels.
2. Circumferential welding on such objects as torque tubes and axle housings.

The electrode is usually moved for:

1. Longitudinal seams of tanks and pressure vessels.
2. Large structures, such as heavy girders, center sills and ship plating.
3. Irregularly shaped structures for which the electrode must travel in a definite contour or at different speeds.
4. Thin metal structures, because of the elaborate jigging and clamping necessary to hold the work.

(*C*) *Welding Data.*—Welding speeds on butt and fillet welded joints made with bare, wash-coated or dust-coated types of electrodes are given in Table 1. These values are welding speeds only and do not take into consideration the time required to set up the parts and remove them from the welding fixture.

Table 1—Automatic Welding Speeds—Bare Type Electrodes

Plate Thickness	Joint Design	Electrode Diameter	Current, Amp.	Passes	Speed, In./Min.
18 gage	Square butt	1/8	110–180	1	25–33
16 gage	Square butt	1/8	125–200	1	20–28
14 gage	Square butt	1/8–5/32	150–210	1	18–26
12 gage	Square butt	5/32	160–225	1	16–24
10 gage	Square butt	5/32	180–230	1	12–20
8 gage	Square butt	3/16	225–280	1	10–17
3/16 in.	Square butt	3/16	225–300	1	8–13
1/4 in.	60° single vee	3/16	225–300	2	5–8
3/8 in.	60° single vee	3/16 and 1/4	240–325	2	3–5
1/2 in.	60° single vee	3/16 and 1/4	240–350	3	2–3
5/8 in.	60° single vee	3/16 and 1/4	240–350	4	.8–2.5
3/4 in.	60° single vee	3/16 and 1/4	240–350	5	1.5–2.0
1/4 in.	Fillet weld	3/16	200–280	1	16–19
5/16 in.	Fillet weld	3/16	200–280	1	11–13
3/8 in.	Fillet weld	1/4	250–300	1	8–10
1/2 in.	Fillet weld	1/4	250–300	2	5.8–6.5
3/4 in.	Fillet weld	1/4	260–325	3	2.5–3.0

Typical butt welding speeds obtained with the impregnated tape type of automatic equipment are given in Table 2.

Table 2—Butt Welding Speeds—Coated Electrodes

Electrode Size, In.	Plate Thickness, In.	Welding Current, Amp.	Speed, In./Min.
1/8	3/32–3/16	150–220	18–45
5/32	1/8–1/4	170–250	15–45
3/16	3/16–3/8	230–330	10–30
1/4	5/16 and up	300–500	8–24

Travel Mechanism

1. It is important that the motion be smooth, otherwise non-uniformity of bead results.

2. A continuous speed adjustment is advised. The speed range should vary from 16 to 64 in. per min. for 5/32-in. electrode to approx. 6 to 24 in. per min. for 5/16-in. electrode.

3. Provision should be made to start the travel motor after the arc is established and stop it before it is finally extinguished to permit filling of the crater.

4. If there are to be speed changes during the travel, it is advisable to provide a d.c. drive, cutting in and out field resistance to obtain variable motor speed. If a constant operating speed is desired, a.c. induction motor drive with variable speed attachment is satisfactory.

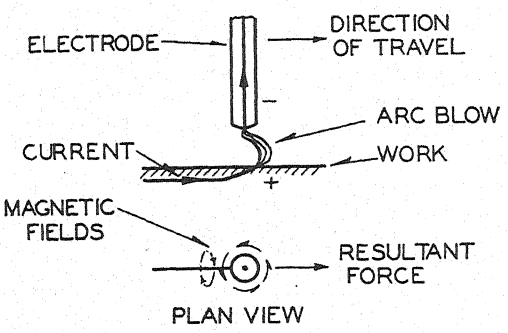


Fig. 3

Automatic welding is obviously most suitable for straight or circular seams. However, the use of specially designed equipment controlled by cams, levers, etc., makes it possible to weld most any shape of seam. Welds around square, elliptical, warped and other shaped members are made in every-day practice.

When welding structures of 3/16-in. metal or under, it is usually desirable to provide clamps and water-cooled backing to reduce distortion. Where excessive fixture wear is encountered, phosphor-bronze is a good clamping material. It is important to keep magnetic materials at least 1 1/2 in. away from the arc in the case of d.c. welding to avoid excessive arc blow.

The ground connection and design of the welding fixture affect arc blow in d.c. welding. It is usually desirable to keep the "blow" ahead of the electrode, i.e., on the same side as the direction of travel of the arc because experience indicates that this gives the best arc stability.

If the current flows in the manner shown in Fig. 3 (negative electrode polarity), the arc will be forced ahead of the electrode. The action of the magnetic field surrounding the current in the work, on that which links the current flowing vertically through the arc, is to force the latter forward. Changing the polarity of the electrode will not change the direction of the force acting on the arc. With a.c. welding arc blow may be ignored.

Special Attachments

In order to make automatic welding adaptable to many types of structures and to increase its flexibility, several important variations of the straight automatic welding process have been developed.

Oscillator.—The movement of the electrode straight along a seam results in the deposition of a bead of weld metal. In many cases a groove is of such a width that it is too wide to use one bead and too narrow to use two beads. In other cases on the finish layer of a weld a series of string beads is not desirable because of their appearance. In both of these cases, the solution is found in weaving the electrode across the joint.

Semi-Automatic Welder.—As mentioned before, the full automatic welding apparatus consists of automatically controlling the arc and the advance of the electrode along the groove. There are many applications, however, when the shape of the seam makes it impossible to cause the electrode to automatically follow it. Semi-automatic welding equipment accomplishes this operation.

Semi-automatic welding is a welding process wherein the arc is automatically maintained, but the electrode is directed along the seam manually. It incorporates many of the advantages of both manual and automatic welding.

The holder or arc end of the nozzle is provided with a fiber handle and trigger switch to start and stop the arc and electrode feed. The welding current enters the electrode through the sliding contact in the rigid nozzle portion at the holder.

Semi-automatic welding offers the flexibility of manual welding with the increased welding speed and quality of automatic welding. It removes the responsibility of maintaining the proper arc length from the operator and greatly increases the welding speed.

CHAPTER 4D

AUTOMATIC CARBON ARC WELDING*

Field of Application, Advantages, Equipment, Carbon Electrodes; Shielding During Welding, Control of the Carbon Arc, Welding of Steels, Procedure and Production Data, Types of Joints, Welding to Code Requirements, Estimating Cost, Aluminum and Its Alloys, Physical Properties of the Weld Metal, Copper and Its Alloys, Low Alloy—High Tensile Steels, Stainless Steels.

Field of Application

AUTOMATIC shielded carbon arc welding finds its greatest applications to articles whose production is sufficient in amount and of relatively uniform character such as tanks, certain automotive and refrigerator parts, pipe, boilers, steel barrels, ships and barges. The process is used for joining many types of metal such as all of the weldable steels, copper and its alloys, the stainless steels, and aluminum and its alloys.

Advantages of Automatic Carbon Arc Welding

Advantages of the automatic carbon arc process, in addition to high speed of welding are: (1) independent and separate controls of (*a*) arc voltage, (*b*) arc current, (*c*) travel speed, (*d*) filler metal both as to amount fed in and analysis, (*e*) flux as to amount; (2) absence of metallic spray and spatter; (3) use of square-edged plates rather than specially prepared joints; (4) flexibility and adaptability for varying gage thicknesses of all types of weldable metals; (5) economy of the process inasmuch as the base metal oftentimes makes up the entire material for the welded seam; (6) ease of shielding the molten metal during welding; (7) the arc may be changed from a non-penetrating to a gouging arc by superimposing magnetic fields in or adjacent to the welding boot; (8) no filter metal need be used where flush joints are required—thus saving grinding and finishing of the welds; (9) warpage is reduced due to controlling the heat in the base metal during welding.

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* Prepared by a committee consisting of A. F. Davis, The Lincoln Electric Co.; H. C. Boardman, Chicago Bridge & Iron Co.; A. J. Deacon, Bethlehem Steel Co.

Equipment for Automatic Carbon Arc Welding

The carbon arc for welding requires a direct current welding generator usually of the variable voltage type. The polarity of the carbon is always negative, and the work positive.

The welding head is a motor-driven mechanism for holding and feeding the carbon electrode. It automatically strikes and maintains the arc at any desired arc voltage setting. An electromagnet is used to stiffen and direct the arc blow; this also tends to agitate the molten metal facilitating the exodus of non-metallic inclusions and gases from the weld metal.

Suitable provision is made for feeding the fibrous or powdered shielding material. Either can be fed with or without filler metal. A complete welding head is shown in Fig. 1.

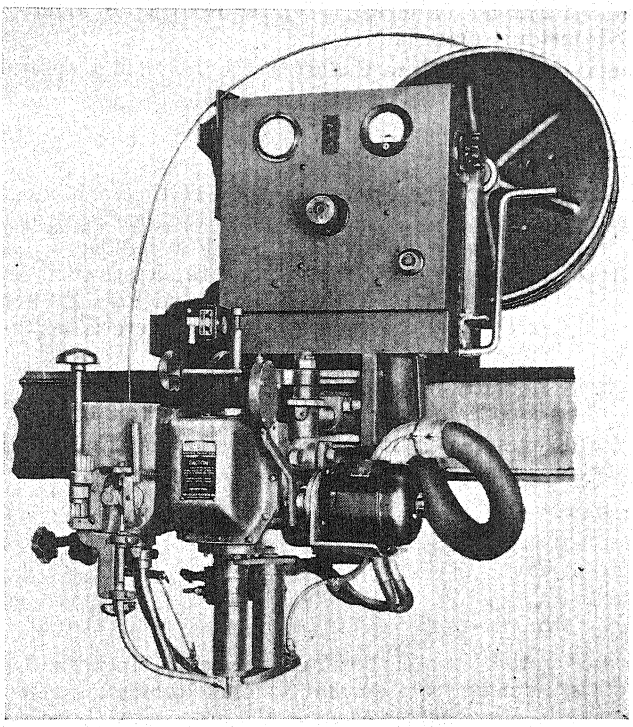


Fig. 1—Automatic Carbon Arc Welder Containing Carbon Electrode and Mechanism for Feeding the Fibrous, or Powder, Shielding Material as Well as Filler Metal

This process can be adapted to any particular application where considerable welding of uniform character is done. In some applications the welding head is mounted on a carriage and travels on a beam, welding the seam while the work remains stationary under it. The set-up consists of some simple fixture for holding the work and a power-driven fixture for moving the welding head along the seam.

In other applications, the welding head remains stationary while the work moves under the carbon arc. In this instance, the welding head is mounted at the proper distance from the work while the fixture moves the work along under the arc. In a third type of application, the welding head is mounted on a self-propelled tractor, which travels along the seam. This type of welder is used in welding pipes, tanks, vessel tank tops, barges, battledeck floors, etc.

The automatic welding head maintains the carbon electrode at any desired pre-set voltage by means of its specially designed electrical control.

The carbon electrode is fed through a water-cooled magnetic boot and is revolved during welding. The turning of the carbon is desirable to maintain a uniform point and to self-clean the bushing where the current contact is made.

Protection of the molten metal, when required, is by means of slag and gas types of shielding material.

Filler metal may be fed into the arc as the particular applications warrant.

Carbon Electrodes

In automatic welding, the exposed portion of the carbons is kept relatively short—$1^1/_4$ to 2 in. This permits the use of greater current densities for a given diameter than is the case in hand use. Also the life of the electrodes is many times longer due to the lesser surface exposed to oxidation below the contact. Most carbons used for automatic welding are of the coke, rather than graphitic type, as there is no apparent advantage of the latter.

The electrode sizes most commonly used are $^1/_4$ in., $^5/_{16}$ in., $^3/_8$ in., $^1/_2$ in. and $^5/_8$ in. The lengths may be anywhere from 12 to 36 in.

The current ranges, depending on thickness of plate and character of the work to be welded for the various sizes, are as follows:

Diameter, In.	Current Range, Amp.
$^1/_4$	50- 350
$^5/_{16}$	100- 700
$^3/_8$	150- 900
$^1/_2$	200-1100
$^5/_8$	250-1400

The burn-off rate of the carbon in inches per minute is dependent on several factors, namely: (1) current—higher amperage, faster consumption; (2) voltage—the shorter the arc the faster the burn-off rate; (3) type of shielding—the gas type retards oxidation of the hot carbon; (4) distance of the exposed carbon from the area of current contact; (5) current density in relation to the cross section of the electrode. The burn-off rate varies from $^1/_{16}$ to $^1/_2$ in. per minute.

Shielding of the Carbon Arc During Welding

The protection of the molten metal from the atmosphere is accomplished by gas- and slag-forming fluxes introduced into the arc by means of an automatic feeding mechanism attached to the welding head.

There are three types of fluxes used. These are: paste type for light

slag forming; fibrous type in the form of a chemically impregnated paper cord; and powder type, heavy slag forming.

The light slag-forming fluxes are mixed with water and brushed on the seam prior to welding. There are several types used, each being designed to suit the chemical analysis range of base material or type of joint. They are used when welding voltages are from 19 to 25 volts.

The paper cord flux produces a gaseous shield which protects the metal from oxidation. It also performs the function of stabilizing the arc. The thickness range of steel is 16 ga. to $^5/_{16}$ in. Paste type fluxes may be used with fibrous fluxes. Fig. 2 is a diagrammatic sketch showing fibrous cord being fed into the arc.

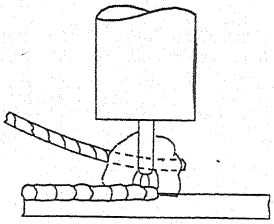


Fig. 2—Carbon Arc—Superimposed Magnetic Field—Shielded

Powdered fluxes are used for plate thicknesses $^1/_4$ in. and heavier where the amount of heated metal exposed to the atmosphere is greater than in thinner material. They produce a layer of heavy slag over the bead. Special powdered fluxes are also used for aluminum and stainless welding. The powder flux feeder can be seen in Fig. 1.

Control of the Carbon Arc

The carbon arc is very easily affected by the magnetic fields set up from the welding current and the distribution of magnetic material in the particular piece being welded. In order to stiffen and focus the arc in a desired direction a separate magnetic field is used. These magnetic fields are generally built into or around the welding boot through which the carbon feeds.

The three types of control most generally used are: (1) the alternating current boot; (2) the direct current boot; (3) the twin tornado boot.

The effects of magnetic fields on the carbon arc can be noted in Figs. 3

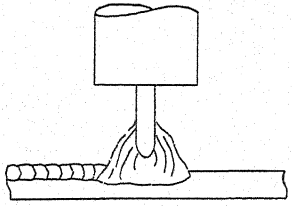


Fig. 3—Carbon Arc—No Magnetic Field—No Shield

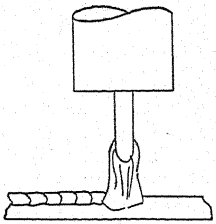


Fig. 4—Carbon Arc—Magnetic Field Superimposed—No Shield

and 4. The effect of these magnetic fields upon the arc is lessened as the height of the boot is raised above the work.

The alternating current boot is one in which the field is produced by a shunt coil energized generally from 110-volt supply. It is used for welding light-gage material and also where the symmetry of the iron about the seam is not uniform.

The direct-current boot is energized from the welding current. It is used for welding butt and lap joints of the medium gage materials. The penetration for a given current and speed is about 20% greater than the alternating current boot and width of the weld is about 20% less.

The twin tornado, which can be seen in Fig. 1, consists of a welding boot and a magnetic boot with adjustable pole piece. These boots are connected in series and are energized by the welding current. They are arranged to produce a backward flow of the arc so that the force of the arc tends to propel the molten metal away from the carbon toward the point of solidification. It is used with powdered fluxes in making butt welds in material $^1/_4$ in. and heavier.

CARBON ARC WELDING OF STEELS

Quality of the Weld Metal

The assumption is often made that when welding with the carbon electrode, the carbon content of the weld is higher than the base metal. This would be true only if the carbon actually contacted the molten metal, which, of course, is not the case. Table 1 gives comparative carbon content of base metal and weld metal.

Table 1
Typical Carbon Analysis of Weld Metal and Base Metal

Low, Medium and High Ranges	Carbon Content	
	Weld Metal	Base Metal
Low (0.07–0.12)	0.06	0.10
Medium (0.15–0.25)	0.11	0.20
High (0.30–0.40)	0.15	0.35

Table 2
Properties of Weld Metals and Mild Rolled Steel

Material	Tensile Strength, Psi.	% Elongation in 2 In.	Density, Grams per Cc.	Endurance Limit,* Psi.	Notched Bar, Ft-Lb.
Weld metal made with shielded arc	55,000–75,000	20–40	7.84–7.86	28,000–32,000	25–80 (Izod)
Mild rolled steel	45,000–65,000	20–40	7.86	24,000–28,000	20–80 (Izod)
Weld metal made with bare or washed electrode	40,000–55,000	5–10	7.5 –7.7	12,000–15,000	8–15 (Izod)

* Maximum stress in outside fibers, 10 million reversals without failure. Rotating beam test.

It can be readily seen that the automatic carbon arc process, which maintains a desired arc voltage, which has control of the arc blow, and which provides for proper shielding of the molten metal, produces welds of uniform high quality, as shown in Table 2.

Procedure and Production Data for Automatic Welding with Shielded Carbon Arc

The tables on the succeeding pages give the welding data for various types of joints and metal thickness. The information includes the current, voltage and speed settings together with the type of fluxing materials and where necessary the amount of filler metal required.

The speeds as given are for pressure tight welds. These speeds can be increased from 50 to 200% for commercial welding. The maximum speed, and consequently, most economical welding is obtained by adherence by management to the following conditions:

1. Use of steel best suited for welding and uniformity of classification. In other words it would reduce welding speeds to have parts of 0.05% carbon mixed with steel of 0.30% carbon.

2. Uniform fit-up—otherwise welding procedures cannot be kept constant—and speed will necessarily be reduced. The data are based on a gap of not more than 10% of the plate thickness, but in no case more than $^1/_{32}$ inch without backing or $^1/_{16}$ inch with backing. If the gap without backing is greater than the above, it should be sealed with a fast hand bead prior to welding. The offset of the edges should not be more than 10% of the metal thickness.

3. Best fixture design which will eliminate variables of fit-up, arc blow and foreign matter from the seam.

Current—It must be remembered that the current given is approximate—and will of necessity be altered by the amount of reinforcement, fit-up, type of steel and surface condition.

Fluxing—The shielding as explained previously is accomplished by paste, fibrous or powdered fluxes—and is so indicated in the table.

Paste Type—is mixed with water and brushed on the seam.

Fibrous and Powdered Types—are fed automatically by the welding equipment.

It is also well to appreciate that the arc voltage, current, speed of travel, type of flux, and amount of reinforcement may all be changed independently of each other to meet specific application requirements.

The following is divided into commercial and code welding and the data are given only as a guide for welding procedures. Speeds and costs for the various types and thicknesses of joints may vary depending upon requirements. Each problem should be worked out in detail, and with care, to take full advantage of all conditions.

Commercial Welding

Material—plain carbon steel of good welding quality. The following procedure is intended for straight seams.

Butt Welds—Filler Metal Added—Work Clamped in Position on Copper

Backing—Fibrous Flux.—For this type of a weld a filler wire automatically fed into the arc is recommended (see Fig. 5)—used in making tanks, range boilers, pipe and similar products.

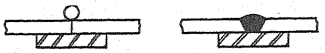


Fig. 5

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Filler Metal, Lb. per Hr.	Welding Speed, Ft. per Hr.
16 ga.	42	180	5/16	Fibrous + paste	5	160
14 ga.	42	240	5/16	Fibrous + paste	5	160
12 ga.	42	300	5/16	Fibrous + paste	5	140
10 ga.	42	375	5/16	Fibrous + paste	5	100
3/16 in.	38	375	3/8	Fibrous + paste	5	75
1/4 in.	38	400	3/8	Fibrous + paste	5	60
5/16 in.	38	450	3/8	Fibrous + paste	5	45

Where welds of higher quality are required the powdered flux is used rather than the paste and fibrous types.

Butt Welds—Filler Metal Added—Work Clamped in Position on Copper Backing—Powdered Flux.—See Fig. 5.

Metal Thick-ness	Arc Volts*	Arc Amp.	Carbon Size	Type Flux	Filler Metal Lb. per Hr.	Angle Degrees†	Welding Speed, Ft. per Hr.
3/16 in.	28–33	700	1/2	Powder	9.0	Horiz.	95
1/4 in.	28–33	750	1/2	Powder	9.0	Horiz.	85
5/16 in.	30–35	750	1/2	Powder	8.5	3	70
3/8 in.	30–35	750	1/2	Powder	7.5	3	45
1/2 in.	31–36	750	1/2	Powder	6.5	4	25

* When welding high-tensile steels use the high side of the voltage range. A copper backing strip with a 1/4 x 1/16-in. groove is recommended when the metal thickness is 3/16 in. or more.

† When an angle is specified it indicates the angle of tilt from horizontal at the point of welding, so the welding progresses up the incline.

Butt Welds—No Filler Added—70% Average Penetration.—The seams are tightly clamped together without backing. The joints may be prepared as shown in Figs. 6 or 7. Automobile axle housings, motor and generator frames, ship channels and many other products may use this type of joint.



Fig. 6

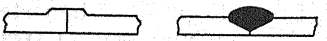


Fig. 7

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Welding Speed, Ft. per Hr.
16 ga.	22	200	5/16	Paste	300
14 ga.	24	250	5/16	Paste	300
12 ga.	24	350	5/16	Paste	260
10 ga.	24	375	5/16	Paste	180
3/16 in.	35	400	3/8	Fibrous + paste	150
1/4 in.	38	450	3/8	Fibrous + paste	120
5/16 in.	38	450	3/8	Fibrous + paste	100
3/8 in.	38	450	3/8	Fibrous + paste	75

If the steel conforms closely to the recommended steel for good welding quality, the current recommended for 14 ga. to 3/16 in., inclusive, may be increased up to 450 amp. with a corresponding increase in welding speed.

Butt Welds—Filler Metal Added—70% Average Penetration.—The tabulated data below are based on seams being tightly clamped together without backing. The use of filler wire automatically fed into the arc is recommended. This type of joint, Fig. 8, is somewhat stronger than those illustrated in Figs. 6 and 7 and is used on automobile torque tubes, railroad car center sills, etc.



Fig. 8

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Filler Metal, Lb. per Hr.	Welding Speed, Ft. per Hr.
14 ga.	42	160	5/16	Paste	3	260
12 ga.	42	200	5/16	Paste	3	200
10 ga.	42	290	5/16	Paste	3	160
3/16 in.	36	375	3/8	Fibrous + paste	5	140
1/4 in.	38	450	3/8	Fibrous + paste	5	110
5/16 in.	38	450	3/8	Fibrous + paste	5	90
3/8 in.	38	450	3/8	Fibrous + paste	5	65

Butt Welds—Filler Metal Added—100% Penetration—Fibrous Flux.—This type of joint, Fig. 9, is welded from both sides without the use of backing. Filler metal may be rods tack welded on the seam, but filler wire automatically fed into the arc is recommended. If the application permits the omission of filler metal from one side the welding speed may be increased on that side and 50% of the filler metal saved. If the work

is inclined about 5° from the horizontal, the welds can be made at the same speed as shown in the tabulation but the current can be reduced approximately 15 to 20%.

This type of weld is used in the manufacture of pipe, pressure vessels and similar products where 100% penetration is necessary.

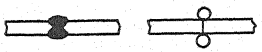


Fig. 9

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Filler Metal, Lb. per Hr.	Welding Speed, Ft. per Hr.
1/4 in.	34	350	3/8	Fibrous + paste	6	50
5/16 in.	36	400	3/8	Fibrous + paste	6	45
3/8 in.	38	450	3/8	Fibrous + paste	6	40

Butt Welds—Filler Metal Added—100% Penetration—Powdered Flux.—See Fig. 9.

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Filler Metal, Lb. per Hr.	Angle	Welding Speed, Ft. per Hr.
1/4 in.	29–34	700	1/2	Powder	9.0	Horiz.	50
3/8 in	30–35	750	1/2	Powder	9.0	Horiz.	50
1/2 in.	30–35	750	1/2	Powder	8.5	3	42.5
5/8 in.	31–36	750	1/2	Powder	7.5	3	35.0
3/4 in.	32–37	700–750	1/2	Powder	6.5	6	22.5
7/8 in.	32–37	750–800	1/2	Powder	6.5	6	17.5
1	32–37	800–850	1/2	Powder	6.5	6	15.0

When welding high-tensile steel use the high side of the voltage range. When an angle is specified it indicates the degree of tilt at the point of welding so the welding progresses up the incline. Powder is used rather than a paste and fibrous flux when higher quality of weld metal is required.

Butt Welds in Heavy Plate.—On plates thicker than 1 in. the joint is prepared as in Fig. 10. Beads Nos. 1 and 2 are made without filler. Filler is added on passes Nos. 3 and 4, the filler being a hot-rolled steel bar of sufficient size to fill the scarf. The welding is done on an angle of about 4° using the powdered type of flux and 700 to 850 amperes.

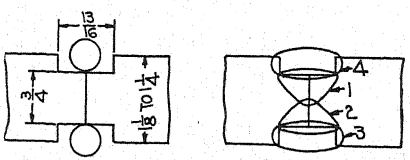


Fig. 10

Lap Welds—No Backing—Work Clamped or Tacked in Place.—No additional filler metal is required in making this type of weld (Fig. 11). Mufflers, tanks, range boilers, ship and barge construction are some of the applications.



Fig. 11

Plate Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Welding Speed, Ft. per Hr.
18 ga.	25	225	5/16	Paste	150
16 ga.	25	250	5/16	Paste	135
14 ga.	26	325	5/16	Paste	125
12 ga.	30	325	5/16	Fibrous + paste	110
10 ga.	32	325	5/16	Fibrous + paste	100
3/16 in.	33	325	3/8	Fibrous + paste	90
1/4 in.	33	350	3/8	Fibrous + paste	70
5/16 in.	35	400	3/8	Fibrous + paste	50
3/8 in.	35	400	3/8	Fibrous + paste	40

Note: If joint is tilted about 5° speeds may be increased as much as 50%.

Where the steel conforms closely to the recommended steel for good welding quality, the above currents may be increased about 75 amp. with a corresponding increase in welding speed.

Edge Welds.—The making of edge welds as illustrated in Fig. 12 requires no additional filler metal, the parts to be welded being simply fused together by the shielded carbon arc.

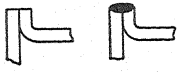


Fig. 12

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Welding Speed Ft. per Hr.
20 ga.	22	120	1/4	Paste	250
18 ga.	22	120	1/4	Paste	225
16 ga.	25	120	1/4	Paste	200
14 ga.	25	140	5/16	Paste	185
12 ga.	25	275	5/16	Paste	170
10 ga.	25	325	5/16	Paste	150
3/16 in.	25	350	5/16	Paste	140
1/4 in.	25	350	5/16	Paste	135

Typical applications include mufflers, tanks, compressor housings, etc.

If the steel conforms closely to the recommended steel for good welding quality the above welding speeds may be increased two or three times with a corresponding increase in welding current provided the current does not exceed 450 amp.

Corner Welds.—The work should be clamped in place on a copper backing where 100% penetration is required. In cases where less penetration is required the backing may be omitted. No filler is required (see Fig. 13). Square tanks, street lighting standards and metal cabinets are typical examples of this application.

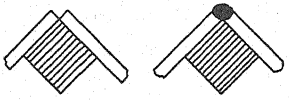


Fig. 13

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Welding Speed, Ft. per Hr.
18 ga.	24	120	1/4	Paste	130
16 ga.	24	135	1/4	Paste	130
14 ga.	24	150	1/4	Paste	130
12 ga.	25	275	5/16	Paste	115
10 ga.	32	325	5/16	Fibrous + paste	100
3/16 in.	32	350	5/16	Fibrous + paste	90

Building Up Shafts and Surfaces.—Filler metal fed automatically into the arc is recommended for applying additional metal to round or flat surfaces as shown in Fig. 14. The speed of travel of the arc will determine the thickness of each layer of deposited metal. Welding at the speeds indicated below will produce a layer of weld metal which will machine clean approximately 1/8 in. thick.

Worn shafting, car wheels and similar items are built up for machining to original size by this method.

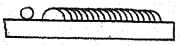


Fig. 14

Shaft Size	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Filler Metal, Lb. per Hr.	Welding Speed, Sq. In. per Hr.
2 1/2 to 6 in. diam.	30	250	5/16	Fibrous + paste	8 1/2	125
6 to 18 in. diam.	30	300	5/16	Fibrous + paste	10	150
18 in. diam. and flat surfaces	32	300	5/16	Fibrous + paste	14	200

Welding to Code Requirements

A.S.M.E. U-68 or U-69

Material: Plain carbon steels which must successfully pass A.S.M.E. homogeneity test.

Analysis:

Carbon	0.10–35%
Silicon	0.20 max.
Manganese	0.90 max.
Phosphorus	0.04 max.
Sulphur	0.05 max.

Some steels outside the above range can be welded satisfactorily at the speeds given below. In some cases it will be necessary to use lower speeds and currents in order to obtain satisfactory results. On the other hand, steels of good welding quality may be welded at higher speeds. The following procedure is intended for straight seams.

Butt Welds—Filler Metal Added—100% Penetration—Powdered Flux.—Welding is done from both sides without backing. (See Fig. 9.)

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Filler Metal, Lb. per Hr.	Angle, Degrees Horiz.	Welding Speed, Ft. per Hr.
1/4 in.	29–34	650	1/2	Powder	8.0	Horiz.	42.5
3/8 in.	30–35	650	1/2	Powder	8.0	1 1/2	32.5
1/2 in.	30–35	600	1/2	Powder	6.5	3	22.5
5/8 in.	31–36	750	1/2	Powder	6.5	3	17.5
3/4 in.	32–37	700	1/2	Powder	6.5	6	15.0

Butt Welds—Filler Metal Added—50% Penetration Into Metallic Back-up Bead.

Metal Thickness	Arc Volts	Arc Amp.	Carbon Size	Type Flux	Filler Metal, Lb. per Hr.	Angle, Degrees	Welding Speed, Ft. per Hr.
1/4 in.	29–34	650	1/2	Powder	8.0	Horiz.	85
3/8 in.	30–35	650	1/2	Powder	8.0	1 1/2	65
1/2 in.	30–35	600	1/2	Powder	6.5	3	45
5/8 in.	31–36	750	1/2	Powder	6.5	3	35
3/4 in.	32–37	700	1/2	Powder	6.5	6	33

When welding high-tensile steel use the high side of the voltage range. The degree of angle indicates the angle of tilt from the horizontal at the point of welding, so the welding progresses up the incline.

How to Estimate Cost of Making Welds Automatically with the Shielded Carbon Arc

From the data given in the preceding pages, costs of welding the various types of joints and metal thicknesses can be readily secured.

The items used and necessary information are listed below.

Labor—the price of labor for automatic operators varies considerably due to existing conditions of location, etc. The figure used will be $1.00 per hr.

Power—Volts and amperes are given so that the amount of power is known. The efficiency of welders for carbon arc voltage requirements can be taken as an average of 60%. Figure power cost at $0.02 per kwh.

Electrodes—The life of a 13 1/2-in. or 19 1/2-in. carbon will vary from about 3/4 to 3 hr. depending upon various conditions. For a basis of estimating costs the carbon consumption will be figured at $0.10 per hr., since carbon cost per ft. of welding is negligible.

Flux—By consulting the tables, the type of flux used will be noted.

Paste Type—Cost per pound is approximately $0.35 and one pound will cover an average of 300 ft. of seam.

Fibrous—Cost per lb. is approximately $0.30 and there are 60 ft. in a pound. Assume the flux feeds at 8 in. per min., which gives an average cost of $0.20 per hr.

Powder—Cost per lb. is about $0.15 and is consumed at the rate of 8 to 20 lb. per hr. Based on the heaviest to the lightest thicknesses given (where powder is used), the amount will vary in proportion to the speed of travel, for a general cost figure.

Filler Metal—Cost per lb. is approximately $0.075. There are three different sizes used. The tables give the number of pounds per hour.

The number of feet per lb. are as follows:

3/32-in. diam.—43.5 ft.
1/8-in. diam.—24.0 ft.
5/32-in. diam.—15.4 ft.

If closer cost-estimating is desired, consult manufacturer's price list for cost of particular items in quantity brackets purchased. Actual measurements may be taken of consumption of each item for a particular application.

The simplest way to figure direct costs is on an hourly basis and then allow for whatever efficiency factor for the particular application the shop uses. This may vary from 50 to 80%.

Example: 3/4 In. Butt Weld A.S.M.E. U-68 and U-69. Welding from both sides—no backing. Direct costs.

Metal Thickness	Arc Volts	Arc Amps.	Carbon Size	Type Flux	Filler Metal, Lb. per Hr.	Welding Speed, Ft. per Hr.
3/4 in.	34	700	1/2 in.	Powder	6.5	16.5

Direct cost—hourly basis:

Labor @ $1.00 per hr.	$1.00
Power @ $0.02 per kwh. $\frac{700 \times 34 \times 0.02}{1000 \times 0.60}$	0.793
Carbon @ $0.10 per hr.	0.10
Flux—Powder @ $0.15/lb.—$12 \times 0.15$	1.80
Filler metal—5/32 in. diam. @ $0.075/lb.—$6.5 \times 0.075$	0.49
Total cost	$4.183
Cost per ft. $\frac{4.183}{16.5}$	0.254

Note: The above method of figuring costs is based on actual arc time and does not take into consideration idle time or overhead.

AUTOMATIC CARBON ARC WELDING OF ALUMINUM AND ITS ALLOYS

The Automatic Carbon Arc has many advantages in welding aluminum and its alloys where the volume is of sufficient amount and the pieces similar.

Welds made are of high quality in respect to uniformity, appearance and physical properties. The procedure for welding is relatively simple when compared to other means, in that no beveling of joint (up to $^3/_4$ in.) or preheating is necessary and the welds are made by a single pass. After welding it will be found that the slag lifts from the weld leaving a clean, smooth surface which does not require any additional labor to remove any slag that adheres. In case the weld reinforcing is to be removed and polished, it will be found that carbon arc welds require a minimum of labor.

The necessary equipment consists of a carbon arc-welding head with flux and filler metal attachments—energized by a variable voltage d.c. generator; a fixture for holding and backing up the under side of the seam.

Following is a list of aluminum alloys most commonly arc welded:

Type	Al	Cu	Si	Mn	Mg	Fe	Cr	Filler Metal
2S	99–99.4	..	..	..	..	0.6–1.0	..	2S
3S	98	0.11	0.22	1.25	..	0.52	..	2S
17S	Balance	4.0	0.6	0.56	0.55	0.5	..	2S
43S	Balance	0.17	5.0	0.01	..	0.62	..	2S
51S	96.5	..	1.0	..	0.6	..	..	2S
52S	Balance	..	..	..	2.5	..	0.25	2S
53S	Balance	..	0.7	..	1.25	..	0.25	2S

Metal thicknesses of 14 ga. to $^3/_4$ in. may be welded with the carbon arc using a square edge joint.

Up to and including $^3/_4$ in., 100% penetration may be obtained welding from one side against a grooved copper backing strip. The depth and width of the groove vary directly with the metal thickness. For example, on thinner gages the groove would be $^1/_{32}$ in. deep and $^3/_{16}$ in. wide while on $^3/_4$ in. it would be $^3/_{32}$ in. deep and $^1/_2$ in. wide.

When welding the lighter material the metal must be held between top coppers or aluminum alloy clamps and the firestrip with sufficient pressure to keep the bottom copper in contact with underneath side of the seam. The space between the top clamps is varied according to metal thickness so that for 14 ga. it would be $^1/_2$ in. apart while for $^3/_4$ in. it would be $1^1/_2$ in. When welding $^3/_8$ in. the material is tack welded together prior to automatic welding and in this case no top clamps are necessary; only a dam to hold the powdered flux from being blown away by the arc.

The general rule for fit-up is that the gap and offset should not vary more than 10% of the metal thickness; although on heavier plate the gaps may be exceeded somewhat.

Flux

The flux used in all cases is used in powdered form deposited on the seam about 2 in. ahead of the carbon electrode. The quantity of flux used for a specific gage is rather important, as the amount controls to a large extent the outward appearance of the weld, the elimination of porosity and the stability of the arc. Too little flux will produce a rough uneven weld on which is a fused flux which will be hard to remove. Too much flux will vary the penetration and width of the bead.

Filler Metal

The recommended filler metal in all cases is 2S. The filler should be in the unannealed or half hard condition so as to facilitate its feeding through the guide tubes of the filler metal feeder. The rod diameter used is 1/8 to 1/4 in. and is increased with the metal thickness and fed in on the plate slightly faster than the rate of travel. The amount of filler metal is sufficient to give a slight weld reinforcement.

Finishing the Weld

The fused flux under normal conditions comes off easily, leaving a clean surface. If, however, any slag adheres tightly to the metal it should be removed with one of the following methods: (1) wire brush and boiling water, (2) 10% warm sulphuric acid or 5% hot nitric acid for a short time, then rinse with hot water, (3) steam.

If reinforcement of the weld is to be removed, chip nearly flush then either hammer or grind with buffing wheels. Hammering should be used for 2S and 3S only.

Physical Properties of the Weld Metal

Tensile Strength.—Inasmuch as the weld is slightly reinforced the weld will be of sufficient strength to cause the break to occur in the heated zone in the parent metal near the weld, so that in general the strength of the joint is slightly more than the partially annealed strength of the particular alloy. By partially annealed is meant that the rapid chill does not permit the parent metal to reach a fully annealed state.

Table for Butt Welding 100% Penetration Against Copper

Metal Thickness	Arc Volt	Arc Amp.	Flux	Flux Lb. per Hr.	Filler Diam.	Filler, Lb. per Hr.	Speed, Ft. per Hr.	Angle, Welding Up Hill
14 ga.	29–30	190–210	Powder	11	1/8 in.	1.6	110	Horiz.
1/8 in.	32–33	240–250	Powder	12	1/8 in.	1.5	100	Horiz.
3/16 in.	33–34	300–310	Powder	14	5/32 in.	2.0	80	Horiz.
1/4 in.	35–36	350–360	Powder	15	5/32 in.	2.5	70	Horiz.
3/8 in.	37–38	380–390	Powder	17	1/4 in.	3.0	60	2°
1/2 in.	38–39	400–410	Powder	18	1/4 in.	2.75	35	2°
5/8 in.	39–41	440–460	Powder	18	1/4 in.	2.75	30	2°
3/4 in.	42–44	460–480	Powder	18	1/4 in.	3.0	25	2°

Free Bend Ductility.—The ductility of the outside fibers of free bend specimens will vary from 10 to 50% depending on the alloy being welded.

Porosity.—The carbon arc produces welds which are exceedingly free of porosity.

Arc Control.—A.C. Tornado.

Other Types of Joints

Butt joints are the large majority of the seams which are used in design and which can be welded economically with the carbon arc.

Other types of joints (lap, edge and corner) which may be of sufficient uniformity and volume to warrant an automatic, may also be welded.

CARBON ARC-WELDING COPPER AND ITS ALLOYS

The automatic carbon arc process is used extensively for welding copper. When making butt welds the material is clamped on a grooved carbon or copper backing strip. For material 16 ga. to $^{3}/_{16}$ in. this groove should be $^{1}/_{22}$ x $^{3}/_{8}$ in. wide; and with heavier material the depth of the groove is increased to $^{1}/_{16}$ in. When it is essential that the weld be copper, a deoxidized copper filler rod is fed to furnish the desired reinforcement; otherwise a Phosphor Bronze or Everdur type alloy is used because of their free-flowing characteristics. No flux is used, the joint being kept free of foreign material and moisture. The welding and speeds will be comparable to those given in preceding pages for mild steel; but the voltages will be increased to 35 to 45 depending on the thickness of the material, the higher voltages being used for the thicker gages. When welding $^{1}/_{4}$ in. and heavier it will be necessary to preheat if the mass of the material is such that the heat from welding will be conducted away too rapidly.

One of the extensive uses of the automatic carbon arc is for welding end rings on alternating current motor rotors. The welding speeds used will be from 18 to 36 in. per min. depending on the cross section of the end ring.

Procedure for Welding Copper Alloys

Copper alloys such as Everdur 1010, Herculoy and Olympic Bronze are readily welded with the carbon arc. Butt welds are made by clamping the edges securely against a copper backing strip which has a $^{1}/_{32}$ x $^{3}/_{16}$-in. groove. Filler metal, $^{3}/_{32}$ in. in diam., of the same analysis is fed in automatically against the sheet surface ahead of the electrode. The material must be free from scale and other foreign matter. Speeds will be comparable to mild steel for 0.050 to $^{3}/_{8}$ in. thicknesses.

ALLOY STEELS

Automatic Carbon Arc Welding—The Low Alloy—High Tensile Steels

The steels in this classification contain one or more of the following alloying elements: chromium, manganese, silicon, phosphorus, copper,

nickel and molybdenum. The carbon content is kept below 0.30% to reduce their air-hardening tendencies during welding.

Powdered flux is deposited on the seam ahead of the carbon electrode when welding 16 ga. to $^3/_4$-in. material. Generally a mild steel filler metal is used when a weld reinforcement is desired. The arc voltage range will be 3 to 5 volts higher than when welding the straight carbon steels.

Automatic Carbon Arc Welding the Stainless Steels

The 18–8, 25–12 and 25–20 stainless steels are readily weldable with the automatic carbon arc. A powdered flux is used to produce slag protection during welding. The carbon arc process has the advantage in that the weld reinforcement can be controlled to any desired build-up through the speed and size of the filler wire fed against the seam ahead of the carbon. This results in substantially reduced grinding costs—where the weld is finished flush and polished. Material from 16 ga. to $^3/_8$ in. may be welded with the carbon arc. A water-cooled grooved copper backing strip is used for butt welds. The groove permits a slight reinforcement on the inside in case grinding is necessary.

CHAPTER 4E

ELECTRODE COATINGS, WELD METAL AND SLAGS*

Functions of Shielded Arc Coatings, Types of Coated Electrodes, Slags.

FUNCTIONS OF SHIELDED ARC COATINGS

IT HAS long been recognized that welds made with bare or lightly coated electrodes are satisfactory in tensile strength but are low in ductility and resistance to fatigue and impact. This is due partly to the vaporization or oxidation in the arc of essential elements such as manganese, and partly to the presence of oxides and nitrides resulting from atmospheric contamination of the weld metal. Electrode coatings have been developed that overcome these losses and the term "shielded arc coating" has come to include any covering on the core wire which effectively shields both the arc and the weld metal during the entire range of liquefaction and solidification and improves the physical and chemical properties of the weld. A heavy flux coating usually has a number of other advantages.

Kjellberg, of Gothenburg, Sweden, was probably the first to recognize some of these advantages in shielded arc welding. Thirty to forty years ago he experimented with shielded electrodes and found that the tube of coating, like a rifle barrel, guided the molten metal across the arc and the resulting "shotgun wedding" of two pieces of metal was far better than a bare electrode weld. He and later investigators found that the coating:

1. Provides better arc characteristics.
2. Controls the chemical analysis and physical properties of the weld metal.
3. Supplies a protective gaseous atmosphere and slag covering for the weld metal.

These three functions are equally essential in producing sound welds with the exact properties required for each job. Each of these general advantages of shielded electrodes can best be explained by listing the group of related characteristics covered by each of them.

Better Arc Characteristics

Ease of Welding.—Shielded electrodes have less tendency to freeze to the base metal than do bare electrodes and they allow greater variation in

*Prepared by committee consisting of F. J. Aschenbrenner, Arcrods Corporation, *Chairman;* G. H. Chambers, Foote Mineral Co.; J. H. Deppeler, Metal & Thermit Corp.; R. D. Thomas, Jr., Arcos Corp.

arc length. The coating makes it easier to establish the arc when starting to weld and to maintain a steady arc during the entire operation.

Increased Speed.—Greater speed is obtained with shielded arc electrodes than with bare electrodes. This greater speed is due to better arc control and lower thermal losses. Better arc control permits the use of higher currents or larger electrodes. The coating tends to concentrate the heat of the arc on the work causing increased melting rate. The decreased welding time usually more than offsets the time necessary to remove the slag from shielded arc electrode welds.

Polarity Interchangeability.—The composition of the coating determines the best polarity of the electrode. Some coatings operate more efficiently with straight polarity (electrode negative). Other coatings make the electrode more efficient with reverse polarity (electrode positive). Both types have advantages which make them preferable for certain applications. Coatings have also been developed which operate equally well on either polarity, and these types are also efficient in alternating current welding.

Penetration.—The type of coating influences the degree of penetration of the arc and the crater depth, thereby making it possible to obtain, with the proper electrode selection, sound welds in close fitting joints or to avoid burning through on poor fitting joints. The coating also influences the extent of heat penetration and thus affects the extent of recrystallization and annealing of previously deposited layers.

Insulation.—Another useful characteristic of the coating is its low electrical conductivity. This generally permits the use of electrodes in narrow grooves without the trouble of short circuiting the current by the arcing of the sides of the electrode against the base metal.

Better Arc Conduction and Metal Transfer.—The flux coating contains elements which ionize at the temperatures of the arc and form a conducting path between the poles during the periods when the metallic arc is extinguished by the transfer of globules of metal. This steady, ionized arc and the improved type of metal transfer obtained with shielded electrodes are more fully described in Chapter 4A.

Improved Chemical Analysis and Physical Properties of the Weld Metal

Control of Chemical Analysis.—The coating to a large extent controls the analysis of the weld metal either by maintaining the original composition of the core wire or through the introduction of additional quantities of certain elements. Thus manganese is usually included in the coating to maintain in the weld metal the same manganese content that was present in the core wire. In one test the core wire contained 0.51% manganese. A standard coating in which manganese was omitted was used on the wire and the weld metal contained only 0.14% manganese. When 12% manganese was added to the same coating the weld deposit contained 0.41% manganese. The coating may also be balanced to adjust the carbon and silicon content of the weld deposit.

Elements not present in the bare electrode can be introduced through the coating. For example, molybdenum and vanadium may be added to the

coating and these alloy additions will produce better physical properties in the weld metal than those possessed by the core wire.

A Protective Gaseous Atmosphere and Slag Covering for the Weld

The primary reason for the development of shielded arc electrodes was to make possible the deposition of weld metal with physical properties comparable to those of the base metal. The electrode coatings provide a gaseous envelope around the arc and weld metal being deposited, and provide a blanket of molten slag covering the weld. These protect the molten metal from undue oxidation. The extent of gaseous and slag protection depends on the type of coating.

The slag has a number of other functions which may be listed as follows:

1. Acts as a scavenger in removing oxides and impurities.
2. Slows down freezing rate of molten metal.
3. Slows down cooling rate of solidified weld metal.
4. Controls shape and appearance of deposit.

A more extended discussion of welding slags will be found in the latter part of this chapter.

The effectiveness of shielding for mild steel welding is shown in Table 1 giving the comparative physical properties of base metal and of bare electrode and shielded arc electrode weld metal and in Table 2 showing the average chemical analyses of filler metal (core wire) and of bare electrode and shielded arc electrode weld metal:

Table 1

	Bare Electrode Weld Metal	Covered Electrode Weld Metal	Base Metal
Ultimate strength, psi.	50–60,000	60–75,000	55–70,000
Yield point, psi.	38–45,000	45–60,000	30–32,000
Elongation, % in 2 in.	5.0–10.0	20.0–40.0	30.0–40.0
Elongation—free bend, %	10.0–20.0	35.0–60.0	.....
Reduction of area, %	8.0–20.0	35.0–65.0	60.0–70.0
Density, grams/cm.^{3}	7.5–7.7	7.80–7.85	7.85
Endurance limit, psi.	12–18,000	26–30,000	26–30,000
Impact (Izod), ft.-lb.	5–15	40–70	50–80

Table 2

Element, %	Filler Metal (Core Wire)	Bare Electrode Weld Metal	Shielded Arc Weld Metal
Carbon	0.10–0.15	0.02–0.07	0.08–0.15
Manganese	0.40–0.60	0.05–0.25	0.30–0.50
Silicon	0.025 max.	0.025 max.	0.05–0.30
Sulphur	0.04 max.	0.035 max.	0.035 max.
Phosphorus	0.04 max.	0.035 max.	0.035 max.
Oxygen	0.06 max.	0.15–0.30	0.04–0.10
Nitrogen	0.006 max.	0.10–0.15	0.01–0.03

TYPES OF COATED ELECTRODES

In this section, consideration is given to the steel and low alloy steel electrodes of the American Welding Society Specifications A233 for Arc

Welding Electrodes and also to special purpose alloy steel electrodes and stainless and miscellaneous electrodes not included in these specifications. Due to the many types of electrodes and applications, and to the many materials employed in the electrode coatings, the explanations in this section are made to cover only the most common forms of electrodes and their coatings. Important present-day electrode coating compositions are generally held secret by the manufacturers and, therefore, these compositions can be considered only in general terms and various exceptions may exist.

The Classification Numbers of the electrodes which follow are from AMERICAN WELDING SOCIETY Specifications A233 for Arc Welding Electrodes. For detailed specification requirements, refer to Chapter 27.

Lightly Coated, Mild Steel Electrodes

E-4510—Electrodes with Coating Applied Before Drawing, All-Position.—Electrodes of this type are adapted for welding in all positions and are suitable for a wide variety of types of repair and structural welding. The coating contains arc stabilizing materials, but does not provide any important gaseous or slag protection of the weld metal from the air, and, therefore, the tensile strength, ductility, impact values and other physical properties of the deposit are low in comparison to those of shielded arc electrodes. Electrodes of this type are satisfactory only where service conditions are not extremely severe. The electrodes are usable only with direct current and on straight polarity (electrode negative). The arc is characterized by numerous short-circuit periods as relatively large globules of molten metal transfer from the electrode tip to the weld. The arc is not particularly strong and penetration is not great. Since the coating contains practically no slag-forming materials, only a thin scale of oxide covers the finished weld.

This type of electrode is commonly known as a sul-coated or sul-finish electrode. It is often referred to as a bare electrode, although the sul-coating is definitely effective in promoting arc stability. During manufacture of the wire, the steel rod is pickled in acid and held in a spray of water until a desired coating of rust is formed. The rod is then dipped in a lime bath, after which it is dried and drawn to wire. The coating, therefore, consists of a mixture of rust and lime. The lime is the more effective ingredient in promoting arc stability. The quantity of coating is very small. The core wire is usually a plain low carbon steel.

E-4511—Electrodes with Light Coating Applied After Drawing, All-Position.—Electrodes of this type are used for the same types of welding as E-4510. The arc stability is better and the electrodes are somewhat easier to use and produce slightly smoother and more uniform welds. The physical properties of the weld are only slightly better than those of E-4510 because the coating is still designed mainly for arcing characteristics and does not afford adequate protection to the molten metal from the air. Similar to E-4510 electrodes, this type can be used in all-position welding and only with direct current on straight polarity.

The core wire used is often the E-4510 sul-coated wire already containing lime on the surface, although bright finish wire may also be used. The additional light coating is applied by tumbling, dipping or other means.

Of the many coating materials used, the most common are iron oxide and calcium carbonate. The calcium carbonate is the principal arc stabilizing material.

E-4520—Electrodes with Coating Applied Before Drawing, Horizontal Fillet and Flat Position.—Unlike E-4510, this type of electrode is adapted only for flat position and horizontal fillet welding. In comparison to E-4510, this electrode operates with a higher arc voltage and has a very high melting rate, making it impractical for vertical and overhead welding. The amount and fluidity of molten metal are too great to permit its staying in place in these positions. The electrode is usable with high-current densities, making it especially suitable for automatic and high-speed manual welding. The electrode has a decided spray type of metal transfer in the arc which is one of the main factors allowing high travel speeds in welding. The light scale deposited on the weld is readily removed by acid pickling which allows galvanizing without difficulty. This type of electrode is used extensively for the welding of light-gage tanks and drums, and for many other production line assemblies such as automobile frames and parts. The physical properties of the weld metal are similar to those of other lightly coated electrodes as E-4510.

The coatings for this type of electrode are formulated to produce high melting rates with spray-type transfer of weld metal. Most of the coatings are based on titanium dioxide, calcium carbonate and sodium silicate combinations, with various other materials added for specific effects. The calcium carbonate content must be low in order to secure an electrode with a high melting rate. The coating is applied to a bare or pickled rod which is drawn to electrode size, producing a hard and smooth, thin coating. The core wire is low carbon steel similar to E-4510 in analysis.

E-4521—Electrodes with Light Coating Applied After Drawing, Horizontal Fillet and Flat Position.—This electrode overlaps with E-4520 in usage and in operation, although it is generally limited to automatic welding. The wire is usually knurled before the coating application. The knurling provides recesses for the coating and provides more positive electrical contact at the nozzle through the knurl upsets. The electrodes have high melting rates and the spray type of metal transfer, and are satisfactory only for flat position and horizontal fillet welding. The welding characteristics may be considered the same as of E-4520.

The coating materials and core wire may be considered the same as for E-4520.

Heavily Coated, Mild Steel Shielded Arc Electrodes

E-6010—All-Position, Direct Current, Reverse Polarity.—This electrode is the best adapted of the shielded arc types for vertical and overhead welding. It is, therefore, the most extensively used electrode for the welding of steel structures which cannot readily be positioned and require considerable welding in the vertical and overhead positions. Such applications are ships, buildings, tanks, pipe lines and similar structures. The quality of the weld metal is of a high order and the specifications for this classification are correspondingly rigid. The essential operating characteristics of the electrode are:

1. Strong and penetrating arc, enabling penetration beyond the root of the butt or fillet joint.
2. Quickly solidifying weld metal, enabling the deposition of welds without excessive convexity and undercutting.
3. Low quantity of slag, with low melting and low density characteristics so as not to interfere or become entrapped when oscillating and whipping techniques are used.
4. Adequate gaseous atmosphere to protect molten metal during welding.

Electrodes of this type are usable only with direct current on reverse polarity (electrode positive).

This electrode is commonly classified as the cellulosic type. The electrode coatings contain considerable quantities of cellulose, either in a treated form or as wood flour or other natural forms. During welding, the cellulose is ultimately changed to carbon dioxide and water vapor, forming the gaseous envelope which excludes the harmful oxygen and nitrogen of the air. The water vapor from minerals containing water of hydration and that retained by the binder is also liberated.

The slag-forming materials include titanium dioxide and either magnesium or aluminum silicates. Ferromanganese is used as a deoxidizer or degasifier, as it is often classified. Since there is usually no increase in manganese in the weld deposit over that of the core wire, the manganese enters the slag as the oxide. The common binder for the coating materials is sodium silicate solution, which also is a slag-forming material. The core wire is low carbon, rimmed steel, generally of 0.10–0.15% carbon and 0.40–0.60% manganese.

E-6011—All-Position, Alternating Current.—This electrode is intended to have similar operating characteristics and to be used for similar welding applications as E-6010 but with alternating current. The operating characteristics desired are those listed under E-6010; however, this type of electrode has not reached the high-performance level of E-6010 electrodes for vertical and overhead welding because of the inherent difficulty of obtaining a stable and proper functioning arc with high cellulose coatings. This type of electrode, therefore, is usually made with a higher percentage of mineral materials in the coating and as such overlaps considerably with E-6013 more fully described later.

Electrodes of this classification have not been developed and marketed to the extent of many other types. The desired coating would appear to be that of E-6010, but with materials present to provide a stable and quiet arc with alternating current. Since most electrodes classified as this type may be more accurately classified under E-6013, the coatings will be explained later.

E-6012—All-Position, Direct Current, Straight Polarity.—This type of electrode is often referred to as a "Poor Fit-Up Electrode" because of its ability to bridge wide gaps in joints. It is particularly well adapted for single-layer welding of horizontal fillets. This type is very extensively used in most types of steel fabrication because it offers economy due to ease of use and high welding speeds. As can be seen from the requirements for physical properties in the AMERICAN WELDING SOCIETY Specifications A233, the ductility of the weld metal is not as high as of most other types of heavily coated electrodes. The usual operating characteristics of this type of electrode are listed as follows:

1. Suitable for use with direct current, with either straight (electrode negative) or reverse (electrode positive) polarity, and with alternating current. Straight polarity is preferred because of a more direct and stable arc.

2. Adequate penetration in order to reach the root of fillet and other joints, but not as deep penetration as with E-6010 in order to enable the filling of wide gaps without burning through. The small diameters, as $^3/_{32}$ in. and $^1/_8$ in., are especially adapted for sheet metal welding without tendency to burn through the sheets.

3. The slag is more abundant and covers more of the molten pool than those of E-6010 types, but is not as abundant or as fluid as those of E-6020 and E-6030 types. The slag solidifies very rapidly just below the freezing point of the metal. The slag is generally dense and close fitting to the deposit.

4. The molten metal may be considered slightly more fluid than that of E-6010 type, but not to the extent that this electrode cannot be used in all-position welding. The molten metal and slag characteristics control the shape of the weld deposit and make the electrode especially suitable for horizontal fillet welding, producing flat or slightly convex beads without undercutting. Many of the electrodes of this type are suitable for vertical welding in the downward direction, although, for some purposes, the penetration and throat thickness are insufficient. In vertical welding in the upward direction, small welds are more convex and with wider spaced ripples than with E-6010 electrodes. When welds are large enough to permit the deposition of a substantial shelf upon which to continue, the shape and appearance are more satisfactory.

From the coating standpoint, this electrode is often known as the Rutile Type. Probably all electrodes of this type contain rutile, a titanium oxide mineral, as the primary slag-forming constituent. In addition to rutile, various siliceous materials, such as feldspar and clay, are used. Since the electrode depends mainly on slag for protection of the weld metal, only a small amount of combustible material, usually cellulose, is present. Ferromanganese is the common deoxidizer. Sodium silicate solutions are used as the binder. Calcium compounds are often used to produce satisfactory arc characteristics on straight polarity.

E-6013—All-Position, Alternating Current.—This type of electrode is intended to be similar to E-6012 type, but with improved arc characteristics with alternating current. These improvements are necessitated by the fact that many types of alternating current machines have a relatively low open circuit voltage and demand easily ionized coating materials in the electrode for satisfactory operation. The applications for this electrode are the same as for E-6012. Electrodes of this type also find extensive use in direct current welding where specific properties make them more suitable than E-6012. This electrode is often used to fill the E-6012 classification, being usable in all positions and meeting the physical requirements.

The coatings for this electrode are largely based on those of E-6012, containing rutile, siliceous materials, cellulose and ferromanganese and sodium silicate binder. The important difference is that easily ionized materials must be incorporated which permit the establishment and maintenance of an arc with alternating current at low welding currents and low open circuit voltages.

E-6020—Horizontal Fillets and Flat Positions, Direct or Alternating Currents.—This electrode is designed for the production of flat or concave surface fillet welds in the flat or horizontal positions, with either direct or alternating current. The electrode has numerous applications where very high quality weld metal is required and where work is positioned, such as in the fabrication of pressure vessels, machine bases, gun mounts and

similar structures. The essential operating characteristics are as follows:

1. Usable with either alternating or direct current. It is mainly used with alternating current, but when used with direct current, straight polarity is preferred, especially for the welding of horizontal fillets.

2. The main requirement of the electrode is to produce horizontal fillets of flat or concave surface without undercutting. This necessitates that the molten metal and slag be comparatively fluid, that the metal be quick-freezing, and that the slag continuously cover the back portion of the pool and actually wet the molten metal.

3. Slags of this type are not quick-freezing, but remain as a plastic glass for some time after the molten metal has solidified. The slag and metal are both too fluid to permit general welding in vertical or overhead positions.

4. While specifically designed to meet horizontal fillet welding requirements, the electrode is also adapted to the welding of butt and other flat position joints.

5. The physical properties of welds are of a very high order, especially in elongation. Radiographs show that properly made welds are practically perfect.

This is essentially a mineral coated electrode. The slag coverage is so extensive and the slag-metal reactions are of such nature that the electrode does not ordinarily depend on gaseous atmosphere protection. Volatilization products, such as the water of crystallization of some minerals, are, of course, present. The coating is mainly based on materials which produce an iron oxide–manganese oxide–silica slag. Other constituents containing the oxides of aluminum, magnesium or sodium are present to modify the slag. Ferromanganese is used as the main deoxidizer. The quantities of basic oxides, acid silica and silicates and deoxidizers must be carefully controlled to produce satisfactory operation and good weld metal. Sodium silicate is used as the binder.

E-6030—Flat Position, Direct or Alternating Currents.—This type overlaps with E-6020, but particular attention is given to its use in vee and groove butt welds. It is usually different from E-6020 in that it produces a smaller amount of slag and a less fluid slag, thus decreasing the possibility of slag interference in deep grooves. It is not as suitable for horizontal fillet welding due to insufficient slag coverage of the molten pool. Electrodes of this type are used in flat position welding of pressure vessels and numerous other objects. It is necessary that the weld deposit meet the highest standards of X-ray and physical property requirements.

Essential operating characteristics may be listed as follows:

1. Adaptability for use in narrow or wide groove butt joints, providing adequate slag coverage for weld shape and protection but not slag interference with the arc.

2. Slag must wet metal surface and produce a concave weld within the confines of the groove.

3. The slags are porous and friable, making them very easy to remove. The slags have a hardening range extending considerably below the freezing point of the steel deposit.

The coatings are similar in general to those of E-6020 type, excepting that measures are taken to reduce the amount and fluidity of the slag. The slag is again essentially an iron oxide–manganese oxide–silica combination with alumina, magnesia, sodium oxide and other modifiers. In some electrodes substantial amounts of cellulose are present. Ferromanganese is the principal deoxidizer, although other metals and ferro alloys are sometimes also used. Sodium silicate is the binder.

Heavily Coated, Low Alloy Steel Electrodes

E-7010—All-Position, Direct Current, Reverse Polarity.—This electrode is of a low alloy steel type and deposits metal of approximately 10,000 psi higher tensile strength than the E-6010 to E-6030 types. Electrodes of this classification number are often classed as carbon-molybdenum electrodes because their weld deposits usually contain 0.40 to 0.60% molybdenum. Welding applications are carbon-molybdenum piping for high-temperature and pressure service and many low alloy steels for structural purposes. Electrodes of this type are very similar in operation to the E-6010 type.

The coating materials are of the same nature as those of E-6010, but include ferromolybdenum or other molybdenum-containing materials to provide this element in the weld metal.

E-7011—All-Position, Direct or Alternating Currents.—Plain carbon steel electrodes of the E-6011 and E-6013 types generally meet the physical test requirements of this classification. Their operating characteristics have been previously described. Other electrodes which fall into this classification are of the mineral coated types, but with additional alloying ingredients such as molybdenum in either the coating or core wire. Such electrodes can be used for vertical and overhead welding in $^{5}/_{32}$ in. and smaller diameters. The uses, as for E-7010, are for the welding of carbon-molybdenum and other low alloy steels.

Coatings are either the same as for E-6011 and E-6013, or similar to E-6020 and E-6030 with alloying additions.

E-7020—Horizontal Fillets and Flat Position, Direct or Alternating Currents.—This electrode may be compared directly with E-6020 in all operating respects. As in the case of other electrodes of the E-7000 series, it is used for alloy steel welding where higher tensile strengths or other properties are necessary than are obtained with mild steel electrodes.

The coatings are similar to E-6020, but with additional alloying elements either in the coating or in the core wire.

E-7030—Flat Position, Direct or Alternating Current.—E-7020 electrodes are used for this classification. When others are used, they are similar to the E-6030 types.

The coatings are similar to E-6020 or E-6030, but with alloying elements either in the coating or core wire.

Special Purpose, Low Alloy Steels.—Various low alloy steel electrodes are used to develop specific properties in the weld metal which are characteristic of the alloy used, such as improved atmospheric corrosion resistance, maintenance of impact values at low temperatures and specific heat-treating properties. Many of these electrodes meet the physical requirements of the E-7000 series, but their use is largely confined to welding where the specific properties of the alloy are demanded. These electrodes usually contain the alloys in the core wire, although some may contain the alloys in the coatings. Examples of electrodes which are known to be used include the following steels: medium carbon (0.25–0.45% carbon), copper bearing, nickel, chromium-nickel, chromium-manganese-silicon, chromium-copper, nickel-copper and molybdenum-vanadium.

Coatings for these electrodes are similar in nature and properties to those of E-6010, E-6020 and E-6030 types.

Stainless Steels

The stainless electrodes may be classified in two groups according to the alloy content. The high chrome-nickel, or austenitic, alloys contain at least 17% chromium and 7% nickel. The straight chromium, or ferritic, alloys may be further subdivided into the hardenable alloys which contain 15% chromium or less, and the non-hardenable alloys which contain over 15% chromium. The various alloys in these classes and their uses are completely described in Chapters 19 and 20A.

The stainless electrodes find their chief application for welding alloys of a similar composition. For all of the weldable stainless steel alloy grades there are electrodes which will give a deposit metal of a composition similar to the base metal.

The austenitic type electrodes have recently found wide application for welding low alloy steels, which were previously considered unweldable or weldable only by using special preheats and heat treatments. The application of austenitic electrodes has simplified the welding of many low alloy steels.

Stainless electrodes may be used in all positions. Vertical and overhead welding, however, should not be attempted with electrodes larger than $^{3}/_{16}$ in. as larger electrodes are apt to produce poor welds.

Chromium is readily oxidized by the electric arc, and because of this, stainless electrode coatings contain materials which tend to protect the chromium during its transfer. Gas shielding by the use of cellulose coatings is impossible because carbon may be picked up in the weld metal. Mineral coatings are therefore generally used for stainless electrodes. Highly basic slags are found desirable, which accounts for the use of calcium compounds such as calcium carbonate and other calcium minerals. More recently titanium compounds have been added to provide greater ease of slag removal, a quieter arc, and a smoother weld bead. These gains due to titanium are accompanied by a loss of chromium, which is often compensated for by additions of ferrochromium to the coating. Necessary reinforcements of manganese and silicon are incorporated in the coating to give the weld metal proper deoxidation and the required physical and corrosion resisting properties.

The core wire for stainless electrodes generally contains slightly more chromium than required in the deposit to compensate for the losses through the arc. Certain other elements, such as columbium and, to a less extent, molybdenum, are not fully recovered during arc welding and must have slightly higher percentages in the core wire than required in the deposit.

Miscellaneous Electrodes

Included here are the non-ferrous, high-manganese, cast iron and hard surfacing electrodes. These electrodes do not have the standardization of application, properties and coatings that the mild steel electrodes have, and it is not possible to give complete information covering them. Most of

this group are covered in other chapters and, therefore, will be considered only briefly at this point.

Aluminum.—The common aluminum electrodes are 95% aluminum, 5% silicon alloy core wire, with a heavy dipped coating. Pure aluminum melts at 1217.7°F. and the 95 Al-5 Si alloy melts at a slightly lower temperature. This means that the slag produced from the electrode coating must have a very low melting point to avoid entrapment. Also the slag must be of very low specific gravity and must contain materials to dissolve aluminum oxide formed during welding. Coatings contain various combinations of sodium, potassium, lithium and calcium salts which perform the above functions as slags.

Bronze—Many analyses of bronze are used as electrode cores; however, that most generally used is phosphor-bronze. As in the case of other shielded arc electrodes, essentials of the coatings are that they provide slag of lower melting point than that of the weld metal and that they protect the metal from oxidation. Phosphor-bronze can be used as a bare electrode but with a very long arc, allowing globules of metal to form at the electrode tip and to be transferred separately at close intervals. Such operation is not practical for vertical and overhead welding. The shielded arc coatings largely overcome this operation characteristic of bronze, causing transfer in a more uniform stream of smaller globules and permitting wider range of applications.

High-Manganese Steel.—This type of electrode produces a deposit containing 11 to 14% manganese and usually a smaller percentage of nickel or other alloying elements. It is used for the surfacing and repair of Hadfield high-manganese steels. Electrodes may be either bare or coated. The coated electrodes are usually preferred because of better arc action and higher quality of weld metal produced. Some manufacturers use a core wire containing the manganese, while others incorporate most of the manganese in the coating.

Cast Iron.—Electrodes for welding cast iron include low carbon steel, Monel or nickel, bronze and cast iron as the electrode metal. Low carbon steels, with specially designed coatings, are very commonly used for many repairs of cast iron. The deposit is limited in machinability. The top layers of multiple layer welds may be machined, but the fusion zone area is generally very hard. Monel and nickel electrodes produce metal with good machinability and color match. Certain bronze electrodes may be used for welding cast iron. Coated cast-iron electrodes can be used to produce machinable welds, provided the deposit is high in silicon and sufficient preheat is used.

Hard Surfacing.—This category covers many analyses of electrodes and many applications which are more fully discussed in other chapters. The properties of each type depend on the analysis of deposit and the heat conditions during and after welding. Plain high carbon electrodes, for example, produce high hardness when quickly cooled, but the deposit is softened considerably by slow cooling or annealing. Many of the highly alloyed electrodes retain their hardness at high temperatures. Various electrodes are designed for specific applications combining the desired hardness with corrosion resistance, impact or abrasion resistance or heat-treating properties. The electrodes include bare, lightly coated and heavily

coated types. In many cases, the heavily coated types include essential alloying materials in the coatings.

SLAGS

The heavily coated electrode is often referred to as a slag-coated electrode because of its ability to produce a slag which remains on top of the weld metal. Slags are also produced from bare and dust-coated electrodes, but these slags consist chiefly of iron oxide formed by oxidation of the weld metal and serve none of the purposes usually accredited to slags. The thin slags produced by light dip-coated electrodes perform some of the functions exercised by slags from heavily coated electrodes.

Arc welding has often been compared with electric arc furnace melting. In both cases the charges consist of metallic and slag-forming ingredients. Much of our present knowledge of welding slags has been derived from information obtained from steel melting slags.

Many of the functions of welding slags are identical to the melting furnace slags. In both processes, the metallic and non-metallic ingredients are mixed by the swirling action of an electric arc. In order to produce metal free from slag inclusions, the slag must have the ability to coalesce into large particles and be sufficiently light to float out readily from the metal bath. This property of a slag is controlled by its surface tension which must be low to produce large particles, and by its specific gravity which must be low relative to that of the molten metal.

An equally important function of the slag in both processes is to act as a scavenger. Certain oxides and other non-metallic ingredients may tend to remain in the molten metal bath unless they are dissolved by a slag which will float out. Often the solution of these harmful inclusions is most easily effected by providing a substance which will react chemically with the particle to make it readily soluble in the slag. After the slag has served its purpose by removing non-metallic substance, it prevents further oxidation by the air by forming a protecting blanket over the molten metal.

It is not surprising that many of the first heavily coated electrodes produced slags similar to those found in steel melting furnaces. It soon became apparent that different slag properties were required in welding because of conditions which did not exist in the melting furnace. In steel melting, the time permitted for the slag to carry out its proper functions is considerably longer than in arc welding. Furthermore, the shape of the weld deposit bead and the ease by which slag could be removed from the metal were important factors which had to be considered in developing welding slags. On the other hand, the cost of the slag-making ingredients is a far more important factor in electric furnace melting than in welding electrodes. Also many materials have detrimental effects on furnace linings. Thus a considerably wider choice in materials for designing welding slags is permitted.

In depositing a bead of weld metal it is important that welding slag adheres to the bead until the temperature of the metal is low enough that no severe oxidation occurs. After the weld is cool, it is then desirable that the slag is easily removable from the weld metal. In designing a welding

slag to accomplish these purposes, attention must be given to the coefficient of expansion of the slag in comparison with the weld metal, and the friability of the slag at room temperature in comparison with its friability at oxidation temperatures. Thus, an ideal slag would have a coefficient of expansion differing widely from the weld metal and would remain relatively ductile at high temperatures, and become brittle at lower temperatures.

The welding slag is largely responsible for the shape of the surface of the weld bead which is deposited. For certain applications it is desirable that the bead have a convex contour, whereas other applications require a concave contour. The shape of the bead is largely dependent upon the wettability of the base metal surfaces by the slag. A slag which does not readily wet the base metal will tend to confine the weld bead within narrow limits and produce a convex surface, and, conversely, a slag which wets the base metal will allow the weld metal to spread over the base metal and produce a concave bead.

The welding slag may also control the conductivity of heat from the surface of the weld metal. Too thin a slag may permit too rapid a chill on the top of a weld bead, causing gas or slag to be entrapped and excessive crystalline deformation on top of the weld bead. The ideal condition would be to have a slag which would insulate the weld bead sufficiently to permit most of the cooling to occur by conduction through the base metal rather than by direct radiation from the weld bead.

For certain metals or alloys it may be possible to control the cooling rate of the weld deposit by adjusting the fusion temperature of the welding slag. The freezing of any substance releases a relatively large quantity of heat. The cooling of the metal at a particular temperature may be arrested by giving it a slag which will freeze at that temperature.

For welding in vertical or overhead positions, it is necessary that the slag freeze rapidly in order to hold the weld metal in the desired place. Welding slags for these applications must be carefully designed to have sufficient fluidity at temperatures just above the melting point of the metal for removing gases and inclusions and to solidify rapidly just under the melting temperature of the metal.

The designing of coated electrodes for various applications is influenced not only by the consideration of the slag qualities to be produced, but also by arc stabilization, introduction of alloys, physical characteristics of the coating, and electrode processing problems. It is often necessary to introduce, into what might otherwise be an ideal slag, substances to serve one or more of the above purposes. Electrode coating design becomes, therefore, a process of balancing the various qualities desired against one another in order to obtain the best combination of properties.

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CHAPTER 5A

GAS WELDING*

Fundamentals, Gases Used, Oxygen, Acetylene, Oxyacetylene Flame, Types of Flames, Flame Adjustments, Gas Welding Steel, Multilayer Welding, Filler Metal, Gas Welding Non-Ferrous Metals and Alloys, Fluxes.

GAS welding is a form of fusion welding in which the heat required is supplied by a high-temperature flame produced by burning a mixture of oxygen and a suitable combustible gas. The two gases are mixed in the proper proportions in a welding blowpipe or torch which is designed to give the operator complete control of the welding flame.

Acetylene is almost universally used as the combustible gas in welding because the combustion of a mixture of equal volumes of oxygen and acetylene produces a flame having a temperature far higher than that of any other known gas flame. The temperature of the oxyacetylene flame, estimated to be about 6000°F., is so far above the melting point of all commercial metals that it provides a means for the rapid localized melting that is essential in welding them. The oxyacetylene flame is also used for preheat in cutting, shaping and flame machining of ferrous metals (see Chapter 16) and as a convenient source of localized heat for a wide variety of operations such as hard-facing, flame hardening, flame softening and flame descaling (see Chapter 15).

The oxy-hydrogen flame is used to some extent in welding metals that have low melting points, such as lead and thin aluminum sheet. Other fuel gases, such as natural gas, city gas, propane and butane, have been used to a limited extent for welding.

Fundamentally oxyacetylene welding may be considered as bringing two pieces of metal together and melting the edges in contact by manipulating the oxyacetylene flame produced at the tip of the welding blowpipe or torch. The molten metal will flow until each edge is completely fused with the other. After the metal has cooled, there is a single continuous piece.

In actual practice to assure complete penetration on other than the thinner sections, the edges of the abutting plates are beveled so that a vee is formed and filler metal called welding rod is added to fill up the vee. The angle of the bevel will depend upon the joint being made and the lower edge of the bevel may be broken to form a root face depending upon the

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thickness of the material being welded. Proper manipulation of welding flame and welding rod is essential in order to make certain that thorough fusion is obtained between the metal from the welding rod and the base metal from the faces of the vee.

Warpage due to welding can be controlled or reduced by a number of different methods. Parts to be assembled may be securely tack welded in place before applying strength welds. Then the section least subject to distortion can be welded first, thus forming a rigid structure for the balance of the assembly.

When permitted by design of structure, distortions can be minimized by application of welding on one side of the structure to completion and then on the opposite side in order to partially balance the distortions set up by the heat from welding. Stiff backs or braces can be applied to sections most likely to distort.

Peening of welds can be resorted to in order to dissipate welding stresses and if properly applied can overcome severe warpage. The wandering sequence or step-back sequence method of welding may be used to control residual stresses. This method consists primarily of making short welds with intervening sections left unwelded for a time but later welded after partial cooling of the initial welds.

It is also possible to produce sound, strong joints in metals without actually melting the base metal. Thus, in brazing or bronze welding the edges of the joint are simply heated to a dull red heat by the oxyacetylene flame. With the base metal at the proper temperature and with the aid of a suitable flux, molten metal from a brazing rod will unite with the base metal to form a strong bond. A properly made brazed joint in mild steel is quite comparable in strength to a true fusion weld.

Oxygen

Oxygen is a colorless, odorless, tasteless gas. Its distinguishing characteristic, from the standpoint of welding, is its ability to support and intensify combustion. This characteristic is evident even in air, which contains only about 20% oxygen, the rest consisting of gases that do not support combustion. When pure oxygen is used instead of air, all combustion reactions are greatly intensified and flame temperatures increased. In addition, many substances that do not burn at all in air will burn readily in oxygen. The rapid chemical reaction between red-hot iron or steel and oxygen forms the basis for the oxyacetylene cutting of ferrous metals.

Practically all of the oxygen used for oxyacetylene welding and cutting is obtained from liquid air. Air is about one-fifth oxygen, the rest being nitrogen with a small percentage of rarer gases such as argon, neon and helium. By carefully controlled processes of compression, cooling and expansion, air can be changed from a gas into an intensely cold liquid which is essentially a mixture of liquid oxygen and liquid nitrogen. Oxygen is separated from this mixture by a process known as rectification in which advantage is taken of the fact that liquid nitrogen boils at a lower temperature than liquid oxygen. The rectifying apparatus delivers high-purity oxygen to a storage holder, from which it is compressed into steel cylinders for shipment.

Oxygen is generally shipped compressed to 2000 psi. in seamless steel cylinders which are manufactured and tested in accordance with the regulations of the Interstate Commerce Commission. The size of cylinder in general use for welding contains 220 cu. ft. of oxygen at atmospheric pressure. Cylinders containing 110 cu. ft. are used occasionally.

Each oxygen cylinder must have a valve specially designed to operate at high pressure. This valve has a threaded outlet connection to which an oxygen regulator or an oxygen manifold connection can be attached. Cylinder valves are equipped with a safety device which acts as an excess-pressure release. Excessive heat will increase the temperature of the oxygen and will cause a corresponding increase in pressure within the cylinder. At abnormally high pressures the safety release blows or bursts, and the oxygen escapes to the air.

By means of oxygen manifolds, a number of oxygen cylinders can be connected together. Portable manifolds accommodating up to five cylinders are useful for emergency or occasional heavy welding or cutting work. Stationary manifolds for ten, twenty or more cylinders provide a convenient centralized source of supply from which oxygen can be piped to individual stations throughout the plant or shop.

While oxygen cylinders are very strong and rugged and designed to withstand ordinary handling, they should not be dropped off platforms, knocked about or placed where heavy articles might fall on them. A lifting magnet, rope or chain sling should never be used when moving cylinders; use a safe cradle or platform carrier when hoisting them about.

Cylinders should not be stored in unusually hot places for the reasons given above.

Even at ordinary pressures, pure oxygen is a very active substance. At high pressures its chemical activity is so greatly increased that high-pressure oxygen may combine violently with oil or grease even at ordinary temperatures. For this reason, oil or grease should never be allowed to come in contact with oxygen cylinders or any equipment carrying oxygen under pressure. Oxygen cylinders should never be stored near oil, grease or other combustibles. In using the cylinders, they should not be placed where oil might drop on them from overhead bearings or machines. Oxygen should never be used in pneumatic tools, to start internal combustion engines, to blow out pipe or hose lines, to "dust" clothes or for creating head pressure in a tank of any kind.

Acetylene

Acetylene is a colorless, combustible gas with a characteristic odor. It is a compound of the two elements carbon and hydrogen, and its chemical formula, C_2H_2, indicates that the acetylene molecule contains two atoms of carbon combined with two atoms of hydrogen.

Acetylene from a torch burns in air with a very smoky flame. Mixed with oxygen in the proper proportion, it produces the intensely hot, blue oxyacetylene flame.

Like any other combustible gas, acetylene forms explosive mixtures with air or oxygen. The explosive range with air is from 2.6 to 80% acetylene. Because of this wide explosive range, special care should

always be taken to prevent the formation of explosive mixtures when using acetylene.

Regulations and laws forbid the generation, compression or use of free acetylene at pressures higher than 15 psi. The reason is that acetylene may explode under certain conditions when above this pressure. Pressures of less than this amount are ample for all welding and cutting operations.

Acetylene is produced by the chemical reaction between water and calcium carbide, a chemical compound of calcium and carbon having the chemical formula CaC_2. When a lump of calcium carbide is dropped into water, bubbles of gas rise. The gas is acetylene. After the action has stopped a whitish residue remains in the water; this is hydrated (or slaked) lime. The chemical equation for the reaction is:

CaC_2	+	$2H_2O$	=	C_2H_2	+	$Ca(OH)_2$
Calcium carbide		Water		Acetylene		Hydrated lime

Calcium carbide is a gray, stonelike substance produced by smelting lime and coke in an electric furnace. The product is crushed, screened to definite sizes and packed in airtight steel drums. The standard drum contains 100 lb. of carbide. Several sizes of carbide are available for use in acetylene generators.

Acetylene generators may be classified in two general types, depending on whether the carbide is dropped into the water or the water is allowed to drip on the carbide.

In the carbide-to-water type generator, which is most commonly used in this country, small lumps of carbide are fed from a hopper into a comparatively large volume of water. The heat given off during the reaction is readily absorbed by the surrounding water and the acetylene thus formed bubbles up through the water, being cooled and purified in this way.

While all carbide-to-water generators operate according to the general method outlined above, there is of course considerable variation in mechanical details. Modern acetylene generators for use in welding and cutting are designed to be automatic in operation and as nearly foolproof as possible. When installing and operating acetylene generators, the manufacturer's instructions should be followed exactly.

Acetylene generators for welding and cutting are of two types: low-pressure, in which the acetylene pressure is less than 1 psi. and medium-pressure, which produces acetylene at 1 to 15 psi.

Both low-pressure and medium-pressure acetylene generators are available in a wide range of types and sizes for stationary or portable service. Generating capacities range from 45 cu. ft. of acetylene per hr., or less for a small portable generator, to 6000 cu. ft. of acetylene per hr. at atmospheric pressure for stationary types for large industrial installations.

Acetylene is widely distributed in cylinders. These are quite different in construction from oxygen cylinders, for, as already noted, free acetylene should not be compressed above 15 psi. After much study, the problem of combining safety with capacity was solved by packing the steel cylinders with a porous material, the fine pores being then filled with acetone, a liquid chemical having the property of dissolving or absorbing many times its

own volume of acetylene. In such cylinders, acetylene is dissolved at a pressure of about 250 psi.

Each acetylene cylinder has a valve with a threaded outlet connection for attaching an acetylene regulator. Safety fuse plugs are provided to meet any fire emergencies and the entire construction must satisfy the requirements of the Interstate Commerce Commission. Dissolved acetylene is sold in cylinders having rated capacities of either 100 or 300 cu. ft.

The Oxyacetylene Flame

By means of the various items described later in this chapter the operator can produce at will an oxyacetylene flame of the proper size and character for the work at hand. By changing slightly the proportions of oxygen and acetylene in the blowpipe mixture, the chemical characteristics of the oxyacetylene flame and consequently its action on molten metal can be varied over a wide range.

The complete combustion of acetylene is represented by the chemical equation:

$$2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O$$

which means that 2 volumes of acetylene (C_2H_2) and 5 volumes of oxygen (O_2) react to produce 4 volumes of carbon dioxide and 2 volumes of water vapor. It is evident that for complete combustion, the volume ratio of oxygen to acetylene is $2^1/_2$ to 1.

When acetylene burns in air, all of the oxygen required for combustion is, of course, obtained from the air. In producing the oxyacetylene flame, the acetylene is mixed with an equal volume of oxygen in the blowpipe and the additional $1^1/_2$ volumes of oxygen necessary to complete the combustion are obtained from the air.

Since the mixture issuing from the blowpipe tip does not contain enough oxygen for complete combustion, the following reaction takes place in the zone of the flame right at the tip:

$$2C_2H_2 + 2O_2 = 4CO + 2H_2$$

That is, 2 volumes of acetylene (C_2H_2) and 2 volumes of oxygen (O_2) react to produce 4 volumes of carbon monoxide (CO) and 2 volumes of hydrogen (H_2). It is this reaction that produces the brilliant inner cone of the flame.

In the outer envelope of the flame, the carbon monoxide and hydrogen burn with oxygen from the surrounding air, forming carbon dioxide and water vapor, respectively, as shown in the following two equations:

$$4CO + 2O_2 = 4CO_2$$
$$2H_2 + O_2 = 2H_2O$$

The oxyacetylene welding blowpipe or torch is a device for mixing oxygen and acetylene in such proportions as to produce the tremendously hot welding flame when the mixture is lighted at the tip of the blowpipe. Suitable valves give the operator perfect control over the character of the flame at all times.

Types of Flames

When an exactly one-to-one mixture of oxygen and acetylene is lighted at the blowpipe tip, the resulting flame is called a neutral flame, because there is no excess of either oxygen or acetylene. The neutral flame has two sharply defined zones. The inside portion of the flame consists of a brilliant cone from $^1/_{16}$ to $^3/_4$ in. long. Surrounding this is a larger cone or "envelope flame," only faintly luminous and of a delicate bluish color.

When the oxygen and acetylene proportions are varied from the one-to-one mixture, the character of the flame changes very decidedly.

When there is slightly more than this proportion of acetylene in the mixture, the flame will be found to consist of three easily recognizable zones instead of the two existing in the neutral flame. There is still a sharply defined inner cone and the bluish outer envelope, but between these, surrounding the inner cone, is an intermediate cone of whitish color. The length of this intermediate or excess acetylene cone may be taken as a measure of the amount of excess acetylene in the flame. This flame is variously called an excess acetylene, a reducing or a carburizing flame. When oxygen is in excess in the mixture, the flame has the general appearance of the neutral flame, but the inner cone is shorter, is "necked in" on the sides, is not as sharply defined and acquires a purplish tinge.

Many welding operations require a neutral flame. However, for certain operations the flame may be adjusted so as to be oxidizing or carburizing. An oxidizing flame may be used in the fusion welding of brass and bronze to assist in the formation of a protective oxide film. The use of a slightly oxidizing flame in brazing must take into consideration the possible undesirable effects on the tinning action. For welding mild steels, a neutral flame is desirable while for alloy steels the carburizing flame may be preferable. The adjustments also depend upon the character of the filler rod and the technique to be used should be that recommended for the process.

The type of flame used in welding different material plays an important role in securing the most desirable deposition of weld metal. A shielding medium can be obtained by use of the proper type of flame, with the correct technique of welding, which will reduce the oxidizing and nitrogenizing effect of the atmosphere on the molten metal. It also has the effect of stabilization in the molten weld metal and prevents the burning out of carbon, manganese and other alloying elements.

Proper control of the flame has a great deal to do with securing the required physical characteristics of the ultimate weld deposit.

Flame Adjustments

When some blowpipes are lighted and the blowpipe oxygen and acetylene valves are both opened wide with proper adjustment of pressure, the flame will show a slight excess of acetylene. As the blowpipe acetylene valve is closed gradually, the excess acetylene cone gets smaller and finally disappears completely. Just at this point of complete disappearance the neutral flame is formed. With other types of blowpipes adjustment of the flame to neutral is done by opening the blowpipe acetylene valve wide and then increasing the amount of oxygen until the intermediate cone just disappears.

Excess acetylene flame adjustments are usually given in terms of the ratio between the length of the acetylene cone or "feather" and that of the inner cone, both being measured from the end of the blowpipe tip. Thus, calling the length of the inner cone of the neutral flame adjustment x, a $2x$ excess acetylene flame adjustment would mean that the acetylene feather should be twice as long as the inner cone.

Start with the neutral flame adjustment and increase the acetylene (or decrease the oxygen) until the desired ratio of acetylene feather to inner cone length is obtained.

Similarly, the oxidizing flame adjustment is sometimes given as the amount by which the length of the neutral inner cone should be reduced—for example, one-tenth. Start with the neutral flame adjustment and increase the oxygen (or decrease the acetylene) until the length of the inner cone has been shortened the desired amount. In some cases, as in fusion welding brass and bronze, the exact adjustment has to be determined by the action of the flame on the molten metal.

Oxyacetylene Welding of Steel

As in any fusion welding process, the oxyacetylene welding of steel necessitates a temperature range in the steel adjacent to the weld metal, which temperature range runs from the melting point of the steel to normal base metal temperature—in general, room temperature. Obviously, there is a zone adjacent to the weld above the transformation temperature of the steel, and metal above this temperature is subject to grain growth and on rapid cooling will be hardened.

One of the major metallurgical differences between oxyacetylene and electric welding lies in the fact that the rate of cooling in the oxyacetylene process is entirely under the control of the operator as the amount of heat delivered may be disassociated from the amount of metal melted. In metal electrode welding increase in the amount of heat input results primarily in increase in the amount of metal deposited. Further, the heat generated by the oxyacetylene flame may be applied either directly in the scarf of the weld or at any desired position adjacent thereto, whereas the metal arc is restricted to the scarf and the weld proper. Thus, the normal rapid cooling of the weld by heat conductivity through the plate may be offset by proper application of the oxyacetylene flame, and even when no special precautions are taken to achieve such control the envelope flame blankets the areas adjacent to the weld and materially reduces the rate of cooling. By proper selection of the oxyacetylene flame the operator can control not only the speed of welding but also the rate of cooling of the material adjacent to the weld. This is particularly important when the steels being welded are of the so-called air-hardening type, that is, when the steels respond to relatively slow rates of cooling by hardening. Hardening of the steel is, of course, to be avoided because of the correlative loss of ductility, and in extreme cases because of actual formation of cracks.

The oxyacetylene flame also allows some control of the carbon content of the deposited metal and that portion of the base metal which has been raised to a temperature approaching the liquid state. Use of the oxidizing flame or the presence of mill scale results in a rapid reaction between carbon

of the metal and oxygen, with elimination of the carbon in the form of carbon monoxide. Use of an excessive acetylene flame introduces carbon into the weld metal and in the portion of the base metal at a temperature approaching that of liquid metal.

Manganese and silicon are elements common to plain carbon steel, and they are important in oxyacetylene welding in that they react readily with oxygen when the metal is molten. The reaction product is a very thin slag cover. When the viscosity of this slag cover is properly controlled the molten metal may be readily maintained in position even against the effect of gravity. These elements likewise play an important role in that in the very act of forming the slag cover they react with oxygen thus removing it from the sphere of influence and preventing the formation of the reaction products of oxygen which form blow-holes. The action of these elements in welding by the oxyacetylene process is strictly analogous to their action in steel making. Just as the steel melter employs silicon and manganese to produce clean deoxidized metal under a slag of proper viscosity, so does the welding engineer use them for the same purpose in oxyacetylene welding.

Oxyacetylene welding may be carried out with the torch pointed along the scarf on which the metal is to be deposited—forehand welding—or pointed toward the metal which has just been deposited—backhand welding. Each method has its advantages, depending on the particular application. In general, forehand welding is recommended for material up to $^1/_8$ in. thick as greater speeds will be obtained and the puddle is so small that control thereof is no problem. For material greater than $^1/_8$ in. thick, backhand welding is recommended as it permits increased speeds and better control of the molten puddle. It is realized that the backhand technique has been in general use for only about 10 years, and that a great deal of oxyacetylene welding of $^3/_8$-in. material is still being done by the forehand process. The division in the recommendation at $^1/_8$ in. is a result of careful study and the best opinion of those qualified, based on speeds normally achieved and greater ease of obtaining fusion at the bottom of the scarf. Backhand welding may also be used with an excessive acetylene flame when it is desired to melt a minimum amount of base metal in making the joint. Either forehand or backhand welding is directly applicable to plain carbon and low-alloy steels without the use of fluxes or similar precautions.

Multilayer Welding

The operative and physical advantages of multilayer welding consist of the reduction in the size of the molten puddle allowing it to be worked with less turbulence and consequently less exposure of the molten metal to the ambient atmosphere. The smaller puddle permits ready control in avoiding oxides, slag inclusions, cold shuts and lack of fusion with the base metal. The utilization of multilayer welding on base metal of the larger thicknesses enables the operator in the deposition of the first layer to devote his entire attention to securing complete penetration with freedom from icicles and overheating.

Multilayer welding also increases the ductility of the deposited metal due to the grain refinement resulting from the welding heat of each suc-

cessive layer. In this method the final layer is not subjected to this heat treatment and, therefore, has the same properties as a single layer deposit. This layer can also be refined by use of a progressive torch normalizing pass. In applying the torch normalizing pass, it is recommended that the entire weld be reheated as further grain refinement and improved ductility are obtained.

Multilayer welding can be used in the step-back method or by continuous passes. The former is more economical. The actual details of the application of this improved method of welding to various welding processes will be discussed in the chapters dealing with these problems. In applying multilayer welding, it must be remembered that its major advantage can only be gained by reheating the weld metal through the critical range.

Welding Rods

While there are a number of special welding rods developed for use with the oxyacetylene process in the welding of steel, there are certain common characteristics which deserve emphasis. As metal from the rod forms a large portion of the weld metal it plays an important part in the quality of the finished weld. Good welding rods must be within chemical limits specified by the welding metallurgists and must in addition be free from blow-holes, pipes, non-metallic inclusions and any other foreign matter or "dirt." Good welding rods are designed to give deposited metal of the correct composition. Allowance is made in their chemistry for changes which take place in the welding process. These changes are to be expected, but should occur without undue sparking and spitting and should permit free-flowing metal which will unite readily with the base metal to produce sound clean welds. Steel welding rods are produced in various diameters ranging from $^1/_{16}$ to $^3/_8$ in.; in general, the diameter of the welding rod to correspond to the thickness of the material being welded.

The foregoing emphasizes the fact that the welding rod plays a much more complex role than simply to supply the metal to fill the scarf. With the growth of the welding industry, rods were designed which contain those elements on which the steel manufacturers rely for the initial product of high-grade steel. Silicon and manganese in particular have already been mentioned in this connection. As a consequence the modern oxyacetylene welding rod produces materially stronger and sounder welds than earlier rods.

Oxyacetylene Welding of Non-Ferrous Metals and Alloys

In general the commercial non-ferrous metals and alloys have lower melting points than steel, so that the oxyacetylene flame with its wide range of controlled temperatures is particularly adapted to welding them. Most of the commercial non-ferrous materials contain ingredients such as copper, zinc, aluminum, chromium or silicon which oxidize readily, the oxide being more refractory than the metal proper. Thus fluxes are used in part to protect the metal and in part to dissolve the oxides and remove them from the weld proper.

In general, non-ferrous welding is carried out by the forehand method,

although for heavier sections of material with high melting points, such as copper, backhand technique may be applied. Welding rods for non-ferrous work are usually alloyed to result in a relatively fine grain deposit free from oxide. Sixty per cent copper and 40% zinc is a basic brass composition widely used in the welding of copper alloys. It is usually modified with manganese or silicon or some other deoxidizer to improve flowing qualities and give sounder deposits. Such rods are also used in the bronze welding of steel. In general oxidizing rather than excess acetylene flames are recommended and are used in non-ferrous welding. This is coordinated with the use of fluxes which remain stable under oxidizing conditions.

In the welding of copper if conductivity is an important factor copper base rod with only a small amount of alloying addition is common. The oxyacetylene flame is used to melt the rod and maintain the weld puddle. The alloying agent results in a melting range rather than a strict melting point. By controlling temperature with the oxyacetylene flame so that it lies within the melting range the material can be maintained in a semi-viscous condition so that it can be readily manipulated. This is one of the functions of zinc and tin in the copper base welding rods and silicon in the aluminum welding rods.

Fluxes

The question of fluxes is of special interest. Fluxes are used in the welding and brazing of metals to accomplish the following effects:

1. The flux should remove the oxides which are formed during the deposition of filler metal in the fluid state. The flux should form a fusible slag with the oxides which should float to the top of the molten puddle and not interfere with the deposition of succeeding layers of filler metal. The flux in dissolving and removing oxides purifies the molten metal thereby improving its fluidity and weldability.
2. The flux should also protect the molten puddle from the absorption of and reaction with the gases of the surrounding atmosphere. This effect should be accomplished without interfering with the addition of the filler metal, obscuring the operator's vision or hampering his manipulation of the molten puddle.
3. The flux should clean and protect the surfaces of the base metal and in some cases the filler metal rod during the preheating and welding or brazing periods.

Depending on the application the flux may have one or all the above properties, and it is the balancing of these effects that determines its efficacy. Any one of these functions can be emphasized for a particular purpose at the sacrifice of the others. Regarding the third property noted above, it should be remembered that fluxes should not be substituted for the proper cleaning preparation of the base metal. Other desirable characteristics of fluxes are easy removal upon completion of work and no corrosive action on the finished joint.

Fluxes may be used as a dry powder, a paste or thick solution, or as a coating on the filler rod. When used as a dry powder, the welding rod is heated and then dipped into the powder while the powder may be sprinkled on the base metal. When used as a thin paste, it should be painted on the rod and base metal by means of a brush or dipping. When coated on the rod, protection of the base metal may also be desirable.

The composition of fluxes varies with the particular use intended. Fused borax and boric acids are common bases for brazing fluxes while

alkaline halides are usually present in aluminum fluxes. No one flux is suitable for all types of welding and brazing operations, and recommendations should be solicited from the sources of supply of materials used for the best available fluxes.

Detailed welding procedure and discussion of fluxes used for specific metals are given in the ensuing chapters dealing exclusively with specific metals. In each case the practice follows the principles illustrated in the foregoing.

CHAPTER 5B

GAS WELDING APPARATUS*

Cylinders, Manifolds and Distribution Pipe Lines, Acetylene Generators, Welding Torches or Blowpipes, Cutting Attachments, Regulators, Welding Machines, Accessories.

CYLINDERS

Oxygen

OXYGEN, as marketed for commercial usage, is supplied as a compressed gas contained in seamless steel cylinders. These cylinders are filled to a pressure which is equal to 2000 psi. when the gas contents are at a temperature of 70°F. (The pressure of a full cylinder will increase about 25 psi. for each 5°F. above 70°, or decrease about 25 psi. for each 5°F. under 70°.) Two sizes of cylinders are employed, the most common size containing an amount of compressed gas equal to 220 cu. ft. when measured at standard atmospheric pressure and 70°F.; and a smaller, less common size containing an amount equivalent to 110 cu. ft. at the same standard base pressure and temperature.

All oxygen cylinders in commercial usage are manufactured and periodically tested in accordance with regulations which have been established by the Interstate Commerce Commission for such containers. Each cylinder is provided with a discharge valve specially designed for high pressure service. These valves are equipped with safety devices that will melt or burst to release the contents of the cylinder if the cylinder is accidentally exposed to excessive heat that might otherwise cause its pressure to become excessive, as for example if the cylinder were directly exposed to fire. The valve is usually of forged bronze construction and is provided with a threaded male outlet having the special diameter and thread standardized for such valves by the oxygen manufacturing industry.

Acetylene

Acetylene produced for market purposes is distributed in steel cylinders in which it is dissolved under pressure in acetone, a liquid chemical having a high solubility for acetylene. The acetone solvent is carried in the interstices of a porous material used to fill the interior of the cylinder. This method of charging the acetylene gas into a solvent liquid is employed because acetylene in its gaseous state tends to decompose violently when

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it is compressed to pressures much above 15 psi. In commercial practice, the acetone filled cylinders are charged to a pressure of about 250 psi. Several sizes of cylinders are employed, the most common being those with rated capacities of 100, 275 and 300 cu. ft.

Cylinders for commercial use are made and inspected in accordance with the regulations which have been established by the Interstate Commerce Commission for such containers. Safety fuse plugs are provided to take care of fire emergencies. The cylinder valves are operated with detachable key or wrench type handles, and are provided with outlets having special threads or other design features to avoid the attachment of other than acetylene regulators or acetylene manifold connection leads.

As charging temperatures, acetone content and other filling conditions vary, acetylene cylinders are not charged to a uniform gas content equal to their rated capacities. The purchaser, however, is only billed for the actual acetylene content of the particular cylinder or cylinders shipped to him.

While the gaseous acetylene is readily released from its acetone solvent whenever the cylinder valve is opened to allow its discharge, excessive rates of discharge should be avoided because the resultant rapid effervescence of the gas as it is released from its solvent may result in its entrainment of acetone as a fine mist. To avoid such occurrence, the rate of discharge per cylinder in cubic feet per hour should not exceed one-seventh the *rated* gas content capacity of the cylinder in cubic feet. Where the consumption rate of the apparatus to be used exceeds this recommended discharge rate for a single cylinder, the acetylene should be supplied by two or more cylinders discharging simultaneously through a suitable manifolding device. Apparatus for this purpose is manufactured by most manufacturers of oxyacetylene equipment.

Safety Precautions

While oxygen and acetylene cylinders are strong and rugged and designed to withstand ordinary handling, they should not be dropped off platforms, knocked about or placed where heavy articles might fall on them One should never use a lifting magnet, rope or chain sling for moving cylinders. A safety cradle or platform carrier should be used for hoisting them. Cylinders should be stored where they will be protected from continuous direct rays of the sun or other heat that might cause excessive temperatures. When stored in the open they should be protected from accumulations of ice and snow.

Oxygen cylinders should not be stored near oil, grease or other combustibles and when in use they should not be placed where oil might drop on them from overhead bearings or machines. They should not be handled with greasy gloves or hands, particularly the cylinder valve. Oxygen should never be used in pneumatic tools, to start internal combustion engines, to blow out pipe or hose lines or for creating pressure in a container of any kind.

Acetylene cylinders are provided with safety plugs which melt at about the boiling point of water. For this reason, if the outlet valve becomes clogged with ice, it should be thawed out with warm, not boiling, water

applied to the valve only. A flame should never be used for this purpose. Cylinders stored inside of buildings should be kept in well-protected, ventilated locations away from highly combustible material and away from stoves, radiators or furnaces.

No attempt should ever be made to transfer gas from one cylinder to another, nor to mix gases in a cylinder. Furthermore, no cylinder should ever be used in a set-up where it may be possible for foreign gases or substances to be drawn or blown into it. (Additional safety precautions will be found in Chapter 31 entitled Safe Practises in Welding and Cutting.)

MANIFOLDS AND DISTRIBUTION PIPE LINES

Centrally located supply units with piping systems to conduct the gases to the point of use are a decided advantage where the operations involving the use of oxygen and acetylene can be served from outlet stations on a permanently located piping system. The advantages of such systems are that cylinder and regulator handling are considerably reduced; cylinders are removed from working areas in the shops; a master control of available working pressures is obtained; and a continuous supply of gas is afforded. Systems of this nature have been adopted in many manufacturing plants, jobbing shops and schools.

Users who contemplate adopting or extending such facilities should consult the manufacturers of gases and equipment, and follow the regulations of the National Board of Fire Underwriters, or of the Associated Factory Mutual Fire Insurance Companies, as well as local ordinances.

In the case of oxygen, the centralized source of supply is commonly any desired number of cylinders connected to a discharge manifold. For acetylene, the source may be a limited number of cylinders suitably manifolded, or one or more acetylene generators.

Oxygen Manifolds

These are essentially headers, preferably of non-ferrous metal, having threaded connections, and coiled branches of brass, bronze or copper tubing for attachment to the desired number of standard cylinders. To maintain the necessary continuity of gas flow, the most common type of manifold is designed with an appropriate arrangement of shut-off valves to permit one-half the number of cylinders to be used while the other half is being replaced.

The oxygen is discharged at the point of use through regulators identical or similar to those subsequently described in this chapter, their number and capacity being governed by the requirements of the shop.

Since the manifold, its valves and connections, must withstand full cylinder pressure, its design and construction must embrace approved engineering standards and skilled supervision. Therefore it is advisable for the user to purchase such equipment from reliable manufacturers.

The regulators may be set to deliver any desired pressure within the capacity of the distribution lines. Pressures of from 50 to 100 psi. are commonly chosen, as within this range a large percentage of oxyacetylene operations can be served through pipe of moderate diameters, with freedom from leakage at joints and valves. Excessive discharge pressures would

obviously cause appreciable amounts of oxygen to remain in the cylinders. Where unusually high line pressures and volumes are required, as for very heavy cutting or other special operations, it is usual to employ a separate manifold located close to the work, rather than to operate the entire system at the higher pressure.

Besides the stationary manifolds discussed above, portable manifolds for from two to five cylinders are frequently used at temporary locations or where the demands of one torch or blowpipe are beyond the discharge capacity of one cylinder. These are not designed for attachment to shop piping systems.

The precautions applying to the care and handling of oxygen cylinders should be strictly observed also in regard to all phases of manifold operation.

Acetylene Manifolds

Although having comparable functions and bearing general resemblance to oxygen manifolds in that they involve the use of flexible tubing connections between the cylinders and discharge headers, acetylene manifolds differ in several important respects. They are strictly limited as to capacity unless located in a separate building of specified construction. Headers are required to be of double extra heavy piping not exceeding $1^1/_4$ in. pipe size, and the use of copper pipe, fittings and coils is prohibited. A flash arrester or hydraulic seal is prescribed between the regulator at the outlet and the shop piping, and the pressure delivered to the piping system must not exceed 15 psi. Certain regulatory bodies also specify a flash arrester in each cylinder-connecting coil. As in the case of oxygen manifolds, acetylene manifolds should be purchased from reliable manufacturers, who are prepared to assist in installing the equipment and to instruct the purchaser in its operation.

The nature of the acetylene cylinder with its filler material and solvent, is such that the gas cannot be released from the solvent (acetone) at more than a certain rate, depending upon temperature and pressure. Therefore, the limitations of the manifold are more pronounced than in the case of oxygen, and an attempt to supply the shop piping system from an inadequate number of cylinders will make it appear that the cylinders are exhausted before such is the case. The allowable pressure limit in the lines is 15 psi. so that the situation cannot be corrected except by attaching fresh cylinders or stopping work until the cylinders will release additional acetylene.

Portable acetylene manifolds are generally limited to 3- or 5-cylinder capacity, and are intended for use with one torch or appliance when the consumption of the tip or burner is in excess of the reasonable discharge capacity of a single cylinder. Obviously they are not designed to comply with the regulations applying to manifolds attached to piping systems.

Distribution Lines for Oxygen and Acetylene

In order that the advantages of pipe-line distribution of these gases may be fully realized, it is necessary to observe certain simple principles in the

interest of safety, economy and convenience, and to follow strictly the rules of the regulatory bodies referred to heretofore. The active nature of pure oxygen and the inflammability of acetylene, as well as the value of these gases, make it mandatory to provide pipe lines free from leaks, and protected from accidental damage, and of a size consistent with the service required.

The nature of the apparatus in which oxygen and acetylene are used, specifically the small passages and orifices of welding and cutting tips and the nicely balanced mechanism of regulators, demands that the lines shall be free from contaminating scale or dirt. In the case of acetylene piped from generators, the lines must be properly pitched, and if necessary trapped, to remove excess water that will be precipitated under certain conditions. Provisions should be made for blowing foreign matter out of the lines and where necessary strainers should be used at the outlets. Mention has been made previously of the disadvantages of carrying too high a pressure in the lines; therefore, they should be run as directly as possible, with long sweep bends so that the pressure will suffer a minimum amount of reduction.

Contrary to common belief, the action of pure oxygen on the interior of iron or steel pipe is negligible, and when serious deterioration occurs it is caused by exterior conditions. Therefore, wrought iron or steel pipe is used with satisfaction for both oxygen and acetylene lines. Obviously exterior protection is necessary, its nature being determined by local conditions.

At all points where the gases are drawn off to supply a torch or blowpipe, or other consuming device, a regulator or hydraulic flash arrester is required for the acetylene if the gas is delivered by a manifold or from medium pressure generators, and a regulator should also be provided for the oxygen in the interest of economy. (In a very few exceptional cases, where all the operators are performing identical operations employing the same pressure, the oxygen station regulators could be dispensed with, and regulation be secured at the manifold.) For acetylene from low-pressure generators a suitable waterseal or a hydraulic flash arrester is used at each outlet.

The purpose of the waterseals, and one purpose of the regulators, is to prevent the passage of oxygen back into the acetylene lines. The propagation of any disturbances throughout the system can be prevented by water-seal devices serving each important branch line where it joins the main. All safety devices must be constructed with full understanding of the nature of the troubles to be prevented, and must be maintained in good condition.

Station outlets for welding and cutting should be provided with shut-off valves so that the service regulators can be removed at will, either for repair, or because regulators need not be provided as permanent attachments to all stations at once. Acetylene station outlets are frequently provided with mechanical check valves in addition to the regulators.

Other fuel gases than acetylene may be supplied from manifolds through more or less extensive piping systems. Generally speaking the same rules apply for all such gases, except for certain minor considerations due to their particular characteristics.

ACETYLENE GENERATORS

Acetylene generators for welding and cutting are of two general types: low pressure, in which the acetylene pressure is less than 1 psi., and medium pressure, in which the acetylene pressure produced is between 1 and 15 psi. Both are available in a wide range of types and sizes for stationary or portable service. The small portable generators have carbide capacities from about 15 lb. with generating capacities from about 30 cu. ft. of acetylene per hour. In contrast, some of the large industrial stationary generators have carbide capacities of a ton per hour with generating capacities of thousands of cubic feet of acetylene per hour.

The majority of acetylene generators built and used in the United States are of the carbide-to-water type in which the carbide is fed from a hopper into a comparatively large volume of water. The heat given off during the reaction is absorbed by the water and the acetylene produced bubbles through the water and in this way is cooled and purified. Some portable generators are of the recession type in which the body of water flows toward and makes contact with the carbide as the acetylene is being consumed and recedes or flows away from the carbide when more acetylene has been produced than is required at the moment.

It is advisable to use approved generators that are listed by the Underwriters Laboratories, Inc., or the Factory Mutual Laboratories. Such generators are designed to be automatic in operation and practically foolproof. However, it is extremely important that acetylene generators be installed and operated exactly in accordance with the manufacturers' printed instructions which are furnished with the generators.

WELDING TORCHES OR BLOWPIPES

Torches or blowpipes perform the essential function of producing an oxyacetylene flame that can be completely controlled as to size and characteristics. They have been perfected as to design and performance so that they are simple to adjust and easy to operate in any desired position. While they vary quite widely as to the lesser details of design or appearance, all types have certain fundamental and common characteristics.

The terms "blowpipe" and "torch" mean the same thing: namely, the tool or piece of equipment which mixes oxygen and acetylene and then directs the mixture which, when lighted, provides sufficient heat for welding. In the ensuing paragraphs, to avoid constant repetition, either blowpipe or torch will be used to mean the same piece of equipment.

Welding blowpipes are, in reality, extremely simple devices. They usually consist of a handle, a rear end, two valves, two tubes for the oxygen and acetylene, head end, mixer and tip. The location of the valves at the head or rear end of the handle varies with different manufacturers. There again the size of the blowpipe has a bearing on this arrangement as it is desirable to balance the complete unit as well as possible. For extremely light work where only a small flame is needed and a light weight tip is used, the valves are usually at the front end. On blowpipes for heavy work where long and heavy tips are used, the valves usually are at the rear end.

By means of the valves, the desired proportions of oxygen and acetylene are allowed to flow through to the mixer where they are thoroughly mixed (or intermingled) before issuing at the tip or nozzle. The oxyacetylene flame is produced by igniting this mixture at the tip.

Types

Oxyacetylene torches are of two general types, low pressure and medium pressure. The distinction refers to the acetylene pressure range required for its operation. As discussed in connection with acetylene generators, acetylene at pressure less than 1 psi. is designated as low pressure; from 1 to 15 psi. medium pressure.

Low-pressure torches make use of what is known as the injector principle. Oxygen passes through a small opening in the injector, producing a suction which draws acetylene into the oxygen stream. In principle this may be likened to the Bunsen burner where air is injected or sucked into the gas stream.

In the medium-pressure blowpipe, the oxygen and acetylene are valved at the torch to approximately the same pressure. The mixer serves only to mix the gases thoroughly before they enter the tip.

Mixing Head

The intimate mixing of the oxygen and acetylene gases is accomplished in the mixer. The construction of this part varies considerably according to the ideas of different manufacturers. However, essentially the same thorough mixing results.

The gas passages in the mixer are determined by the size of the orifice in the tip. A small tip will have small holes in the mixer and the larger tips sufficiently larger gas passages in their mixers. Correct use of the proper mixer for a given tip materially aids in eliminating backfires. Numerous tips used today are furnished with the proper mixer as an integral part.

Interchangeable Tips or Heads

Practically all welding blowpipes are provided with a series of interchangeable tips or heads of different sizes so that the same handle can be used on a wide variety of operations. For some types of blowpipes, tip and mixer heads as a single unit are provided. In other cases, only the tip is changed, the mixer being designed to provide mixed gases for a range of tip sizes. In cases where the tip is subjected to considerable mechanical abuse, this latter type is preferred.

The choice of tip size is important because the size of the flame should be large enough to perform the job at hand as quickly as possible, and yet not be so large that burning or other damage may result. As the size of the flame is governed by the size of the drilled orifice of the tip, the recommendations of the manufacturers should be consulted frequently until it becomes instinctive to use the proper size tip.

Care of Torches

The warning "Oxygen—Use No Oil" printed on regulators applies equally well to torches for they use oxygen under pressure. Refer to Chapter 31, "Safe Practices," for further information on this subject of safety in operation.

Before using a new torch for the first time, tighten the packing nuts on the oxygen and acetylene valves. It is customary for some manufacturers to ship torches with these packing nuts loose.

If the orifices in the tips or nozzles become clogged, clean them with the proper size drill or with a soft copper or brass wire. A sharp, hard tool that would enlarge or bellmouth the orifices must not be used. Clean the orifices from the inner end whenever possible.

Selection of Torches

There are a number of types of oxyacetylene welding torches, the choice of which depends on the nature of the work being done. A sheet metal worker will obviously not use the same torch employed in the welding of heavy wall pipe. Proper selection of torch style both as to weight and ability to pass sufficient gas to perform work in hand is important. For very small flames necessary on thin sheets or other delicate work, there are tips available having orifices as small as 0.018 in. The acetylene flow through these tips is only approximately 1 cu. ft. per hour. The torches with which these tips are used are very small and light in weight.

On the other hand, where large sections are being welded and a great deal of heat is needed, tips with orifices as large as 0.250 in. can be secured. Also, there are multiple flame tips that have acetylene consumptions as high as 250 cu. ft. per hour. These latter multi-flame tips are more often used for heating rather than actual welding operations.

CUTTING ATTACHMENTS

A simple attachment which fits into the head of the standard welding blowpipe converts it readily into a cutting blowpipe. This attachment consists of a rear end having a seating arrangement similar to that of the mixer normally used for welding operations. There is a valve to regulate the oxygen to a mixer where it combines with acetylene to form the preheating gas mixture. A separately operable valve is provided to control the cutting oxygen flow. There are usually two tubes for carrying the high-pressure cutting oxygen and the mixed preheating gases to the head which accommodates the cutting tip.

There are many types of work where the main activity is welding, but where cutting has to be done from time to time. In such cases, the welding blowpipe can be easily and rapidly changed into a cutting blowpipe by merely replacing the mixing head with the cutting attachment. As it is unnecessary to disconnect the hose from the blowpipe, the change-over is merely a matter of a few seconds.

Various sizes and styles of cutting tips to suit different types of work are available for the cutting attachment also. Either 75° or 90° angle heads can be used. The use of cutting attachments is not recommended where

constant cutting of thicker materials is encountered. Such work should be done with a regular cutting blowpipe.

REGULATORS

Functions

In oxyacetylene welding and cutting, it is essential that both the pressure and flow of the gases be accurately controlled. These functions are performed by the oxygen and acetylene regulators. The oxygen pressure in a full cylinder is 2000 psi. The acetylene pressure in a full cylinder is approximately 250 psi. Oxygen pressures in pipe lines may run from about 15 to 200 psi. and acetylene pressures up to 12 to 15 psi.

All these pressures must be reduced to suitable working pressures for the torch tip in use. A certain amount of volume regulation is done by adjustment at the torch valves. To reduce the high cylinder pressures to proper working pressures for the torch, to maintain these pressures without fluctuation and to perform these functions automatically, precision instruments are necessary.

General Design

A regulator has a union nipple and nut for attaching to the cylinder and an outlet connection for the hose leading to the torch. There are two gages on the body of the regulator, one showing pressure in the cylinder, the other the working pressure being supplied to the torch. The working pressure is adjusted by means of a hand screw. When this pressure adjusting screw is turned to the left (counter-clockwise) until it runs free, the valve mechanism inside the regulator is closed. No gas can then pass to the torch. As the handle is turned to the right (clockwise), the screw presses against the regulating mechanism, the valve opens and gas passes to the torch at the pressure shown on the working pressure gage. Changes in this pressure are made at will simply by adjusting the handle until the desired pressure is registered. Although the mechanical details of regulator construction vary among the different manufacturers, the fundamental operating principles are the same for all welding and cutting regulators.

Before opening the valve on a cylinder to which a regulator is attached, it is most important to make absolutely certain that the pressure adjusting screw is fully released by turning to the left. As noted above, this closes the valve inside the regulator. The cylinder valve can then be opened.

Types—Single- and Two-Stage

Most regulators today are of either single-stage or two-stage type. Single-stage regulators reduce the pressure of the gases from cylinder or pipe-line pressure to the working pressure of the torch in one stage. In general, its mechanism consists of a floating valve, a diaphragm and balancing springs. These are all enclosed in a suitable housing.

In two-stage regulators, the pressure reduction is accomplished in two separate steps. This type of regulator has two independent diaphragm and valve assemblies which make operation extremely efficient. The full

cylinder pressure enters the regulator and is reduced to an intermediate pressure by the first-stage extra heavy diaphragm with its complement of heavy springs. This first stage is entirely automatic and non-adjustable. The second stage is similar in design to the first stage but has a larger diameter diaphragm and lighter springs. It is adjustable by the operator to any desired working pressure by turning the adjusting screw. Instead of having to carry the full cylinder pressure load the second stage is required to function only within a comparatively narrow range. This dual arrangement of valves and diaphragms insures much more constant delivery pressure adjustment than is possible with single-stage type regulators. The delivery pressure of the two-stage regulator will remain constant throughout the entire pressure range from a full cylinder down to empty.

WELDING MACHINES

For the repetitive production of certain classes of welded articles, machine welding has been found to produce better and more uniform quality and in most cases better economy than hand welding. For work such as the welding of tubing and steel drums or barrels, welding machines are available on the market and used quite extensively. For other machine-welding operations such as the welding of girth seams of washing machine tanks, small shells or cylinders, machines have been built for the particular application. Some of the welding machines are controlled manually by the operator who observes the weld either continuously or intermittently and in other cases the quality of the weld is controlled by an electric eye or photo-cell. More complete information concerning automatic gas welding can be obtained in Chapter 5-C.

ACCESSORIES

Oxyacetylene operations may involve an almost limitless variety of auxiliary equipment including many of the mechanics' common tools, as well as jigs and fixtures for production welding (described in Chapter 32C), guides for straight-line hand cutting, gas savers for automatically shutting off the torch flames when that implement is laid down, devices for impregnating the acetylene stream with liquid flux for brazing operations, and many others.

One of the most universally required articles is the spark-lighter, which in some form should always be used rather than matches to light the torch or blowpipe. For all welding and cutting operations except the most delicate, gloves are an essential protection. They should never be of cotton or other inflammable material. Properly tanned horsehide is preferred for general work, and asbestos for heavy cutting operations where extreme heat and heavy showers of sparks or slag are encountered.

Spectacles or goggles are essential to protect the eyes from sparks and from the strong glare of molten or burning metal, as well as to permit better vision of the work at high temperature. Only such lenses as are of correct composition to intercept a sufficient proportion of the actinic rays of the oxyacetylene flame should be used.

The nature of the work will determine whether any additional articles of protective clothing are needed, such as leggings or aprons. These considerations of eye protection, clothing and health of the operator are covered in Chapter 31 on Safe Practices.

CHAPTER 5C

AUTOMATIC GAS WELDING*

Types of operations and methods in applying gas welding for automatic operation, machines and jigs, continuous and non-continuous, bronze welding, rod feed, gas equipment.

GENERAL

GAS welding may be applied successfully in automatic welding operations through the use of suitable machines and jigs. Applications which are particularly suitable for gas welding are those which require large numbers of uniform pieces with sound welds and where clean surfaces are required. The majority of these applications are found in the fabrication of sheet steel of from about 26 to 14 gage. There are three methods of welding by gas applicable to different operations. These are: fusion welding of steel with and without weld rod and bronze welding of steel with filler rod.

The two general methods employed in handling the stock are the continuous and non-continuous methods. In the former the stock may be fed through the machine in an endless strip as in modern tube welding mills or separate lengths may be fed through end to end as in barrel welding and old style tube welding machines. The continuous method is applicable to straight welds on articles of uniform cross section. Under these conditions, the parts or material to be welded can be fed continuously through a machine carrying the welding head.

In the non-continuous method, the preformed stock is placed in a jig and rotated or translated past a stationary welding head or the jig and material may remain stationary while the welding head travels along the seam on a track. The most common types of welds made by this method are longitudinal, vertical and girth seam welds on round or rectangular vessels.

Strip Welding

There are numerous applications of strip welding to which automatic oxyacetylene welding is well suited. The softness of the weld lends itself to double or triple lengthening of hot-rolled coils before the initial pass in

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the cold reduction mill. In this case, a weld zone that is not appreciably harder than the base metal is required to avoid marring the surface of the cold-working rolls. In addition to softness, the weld strength and ductility must be such as to preclude breakage while going through the cold mill.

Automatic Bronze Welding

The automatic process described above for fusion welding also can be applied to bronze welding. The necessary fluxing action required is provided most conveniently by use of a volatile liquid flux. It may be observed that the bronze-welding application to the fabrication of containers will be more expensive than the fusion welding where the latter can be employed. Although a lower temperature is required for the bronze welding, the more expensive bronze rod more than offsets the heat saving.

In assembling of small parts or attachment of outlets to small containers, automatic bronze welding may be used. This is accomplished through preheating in one or more stages and application of predetermined amounts of bronze rod by mechanized means. In order to avoid cleaning costs associated with the usual solid bronze flux, a volatile liquid flux is generally employed for applications of this nature.

MACHINES AND EQUIPMENT FOR GAS WELDING

In tube welding the preferred type of machine is that in which the flat stock is fed from coils to a forming mill. This mill should be of the roll type with roll forms of a design to give the desired shape.

From the forming unit, the material passes to the welding unit which usually is close-coupled to the forming mill. The welding stand generally consists of at least two sets of horizontally and vertically adjustable, water-cooled, side guide rolls. Preheating and welding take place between these two roll sets. With proper side pressure control of these rolls, the weld reinforcement can be built up or reduced as desired on either the outside, or the inside, depending upon the use for which the tube is intended. Where perfectly flush inside and outside surfaces are desired, scarfing tools are employed to trim the weld.

After passing through the welding and scarfing stands, the tube is cooled in a water spray or bath and sized and straightened in rolls provided for this purpose. Then it is cut off to length in an automatic unit that travels with the tube as the cut is being made and returns to its starting position for the next cut.

For proper operation the design of the welding zone of this type of mill is extremely important. Several factors should be taken into consideration:

1. Upon heating the upper side of the tubing for welding, it tends to expand. This expansion due to differential heating will result in buckling of the edges unless steps are taken to avoid this condition. This may be overcome by providing a slight upward "bow" in the tube while it passes underneath the preheating and welding head. This condition is obtained by having the horizontal holding and welding rolls vertically adjustable. This adjustment should be provided in a manner which will allow it to be varied while the machine is in

operation. This adjustment also provides a ready method of leveling the edges to be welded.

2. The length of weld zone, which is in general the distance from the holding rolls to the welding rolls, will depend upon the following factors:

(*a*) Welding rate. The welding rate will first depend upon the mechanical design or condition of the forming equipment. The speed should not exceed that at which the mill will operate satisfactorily and without undue vibration and at which uniform forming can be obtained.

(*b*) Range of wall thickness to be handled.

(*c*) Ratio of thickness to diameter of tube.

The range of wall thickness to be welded, together with the acetylene supply system capacity, influence the welding rate. Determination of this factor is described on page 224 under "Gas Equipment." At a given speed, the length of the welding zone should vary for the thickness of the metal being welded. Practically, however, it is generally more convenient to select a length which will give best results for the range of wall thickness is to be handled. The speed can then be varied to accommodate the different gages. Where acetylene supply is adequate and mechanical conditions are suitable for high-speed operation, maximum welding rates will go up to approximately 100 ft. per min. for ease of handling. Greater speeds are obtainable with special welding and handling equipment and tubing can be continuously welded from low carbon, stainless and other alloy steel skelp.

Jigs for Non-Continuous Operation

As stated previously, the most common types of welds are the longitudinal and girth seam welds on round or rectangular vessels. When the longitudinal seams are made, the rolled or formed sheet is placed in a clamp with the edges butted together. The weld can be made from either the inside or the outside, depending upon requirements of finish of the completed article. In making this weld, it is preferable to move the welding head with respect to the work. The ends of the container are welded in place next. On round shapes, this girth welding is performed best by revolving the jigs and material beneath the welding head thereby making a flat weld. On rectangular or irregular shapes, the welding head moves around the shape at a uniform rate.

Since no rod is added it is important that the edges be sheared correctly and placed so that the edges to be joined are in contact. This condition can be best assured by the application of side pressure to the clamp jaws in order to force the edges to be welded together. To avoid deformation due to contraction stresses, jigs and clamps used to hold the parts in position should be sufficiently heavy to absorb heat from the work-piece quite rapidly. At high production rates or on small items, it is advisable to provide water cooling in the jigs for this purpose. This type of operation provides a flush weld with a minimum of reinforcement.

A slight variation of this method is applicable to shapes with curved sides that cannot be made by rolling or bending flat sheets. These parts may be stamped or drawn in two halves. These halves are then placed together in a jig and positioned so that seams are in the same horizontal plane. The joints are then welded simultaneously with two welding heads moved by a common carriage. It should be borne in mind that this

method of necessity will proceed at a slower rate than the previously described method, as the horizontal-vertical position of the weld requires a smaller weld puddle.

Heavy Welding with Welding Rod

To obtain full-strength welds on material of 12-gage and heavier, on other than flat sheets, a welding rod is used. The rod feed is made automatic through a variable speed feed mechanism. A single welding head that has several flames so designed as to fulfil the various operations of rod preheat, plate preheat and welding generally is used. This method is suited particularly to the fabrication of cylinders and tanks requiring joints that are leak-proof to dry gases. Drives to provide relative motion between the work-piece and the welding head should be so designed as to preclude the possibility of a non-uniform motion. Means should also be incorporated for varying this speed and the control for this variation should be located close at hand to the operator's station. Likewise, where welding rod is used, a variable speed control to adjust to the proper rate of deposition of the rod should be provided.

GAS EQUIPMENT

In order to obtain the greatest advantage from automatic operation, care in the selection of control equipment is important. In the repetitive operations, valves which control both the oxygen and acetylene simultaneously should be employed. In operations of this type a pilot light will be necessary using either air-acetylene or city or natural gases. Regulator equipment should be selected and maintained so that the pressure of the gases will be the same each time the valves are opened.

The proper design of welding heads is important in securing adequate penetration of the weld without overheating the top surface. In this respect the length of the head should be as long as other factors will allow. In tube welding the length of the head will depend on the following factors:

1. Maximum speed at which the welding machine can be expected to operate without undue mechanical strain.
2. Gage of material.
3. Relation of the gage of material to diameter of tubing.

In selecting a proper size head, it may be computed what hourly acetylene capacity will be required based on the table shown below at the desired welding rate. This hourly capacity then will indicate the welding head size required. However, it should be observed that it is generally not good practice to use a head as long as 15 in. on very light wall, large diameter tubing. In other words, the long head should not be used on 18-gage or lighter material when the diameter is $1^3/_4$ in. or larger, or 20 gage or lighter material when the diameter is $1^1/_2$ in. or larger. For material in this classification better results are obtained with a head 8 or 9 in. long. Furthermore a head of this size will have sufficient capacity to weld up to the usual maximum practical rate of 100 ft. per min. The preferable design for these welding heads consists of a single straight line of flame

ports, the ports being spaced on an average of three-eighths of an inch apart. A somewhat closer spacing is desired over the welding puddle than throughout the rest of the head. The size of these ports may be between No. 56 and No. 66 drill sizes. This type of operation provides a flush weld with a minimum of reinforcement.

The following table gives the approximate consumptions of gases when operating with modern type heads.

Wall U. S. S. Gage	Consumption Cu. Ft. per Linear Ft. of Weld	
	Oxygen	Acetylene
22	0.045	0.039
20	0.075	0.049
19	0.110	0.072
18	0.130	0.085
16	0.180	0.117
15	0.210	0.137
14	0.240	0.156

The figures will vary slightly depending upon the precision of operation of the associated forming mill.

In all cases screw adjustments for the position of the welding head should be provided. These should enable the operator, while in his usual position, and with the machine operating, to raise and lower the welding head and to move it laterally with respect to the weld. An additional angular adjustment is useful in tube welding to twist the head to align it with the seam.

In jig welding, the head length will in most cases be necessarily much shorter and, therefore, the welding rates will be lower. Here a long welding head makes it difficult to provide the proper setting as a considerable lapse occurs between the time when a point on the seam is first introduced under the welding head and when that point is finally welded. Except for very short operations welding heads should be water cooled. The design should be such as to permit rapid conduction of heat away from the welding face of the head.

CHAPTER 6

ATOMIC HYDROGEN WELDING*

Theory, Power Supply, Manual Welding, Apparatus, Operation, Technique, Automatic Welding, Welding Data.

ATOMIC hydrogen welding may be used for practically any application requiring a fusion weld. The operating costs are usually higher than other processes and, for this reason, it is not competitive in certain fields. It finds its greatest usefulness in the solution of special problems which are not readily solved by other methods. The fields in which it finds application are light-gage steel, alloy steels including stainless steel, such of the elemental metals as lend themselves to welding and non-ferrous alloys. Specific applications include the building-up of worn or broken sections of molds and dies, the overlaying of one metal by a different metal for hard surfacing or special problems, and welding light-gage stainless steel.

Theory

Hydrogen in its normal state, called molecular hydrogen to distinguish it from atomic hydrogen, is diatomic. That is, each molecule (the smallest unit into which it may be divided) consists of two atoms. When an arc is established in hydrogen between two tungsten electrodes, the temperature in the arc stream rises to approximately 6000°C. dissociating the molecular hydrogen into its atomic form.

For a clear understanding of the atomic hydrogen process, three points must be kept in mind. First, the energy used for welding is supplied to the arc as kilowatts of electrical energy where it is transformed into heat at a temperature of approximately 6000°C. Second, the establishment of an arc in hydrogen provides a temperature sufficiently high to cause molecular hydrogen to be rapidly transformed to atomic hydrogen, in which state its principal function is as a vehicle for transmitting the heat energy from the arc to the weld zone. Third, in the direction away from the arc stream, a sudden decrease in the temperature, such as occurs at the relatively cold surface of the weld area, is accompanied by a correspondingly rapid decrease in the concentration of atomic hydrogen, and a release of the heat of recombination at or near the cold surface. Thus, it can be

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seen that by varying the distance between the arc stream and the weld surface, the available temperature can be varied over a wide range.

The hydrogen performs several other useful functions. It is a very efficient cooling medium and, by absorbing a large amount of the heat being conducted along the electrode from the arcing end, which is molten, keeps the temperature of the remainder below the melting point. It also prevents air from coming in contact with the heated electrodes, which would cause them to oxidize and consume rapidly. In the same way, it protects the molten pool and the heated metal adjacent to it, reducing the tendency to surface oxidation after the weld is completed.

Power Supply

Alternating current power supply is universally used for several reasons. It is available in practically every manufacturing plant. It is readily converted from any supply voltage to that necessary for welding. The arc being maintained between two electrodes, they will be consumed equally when alternating current is used, but with direct current more heat will be generated at one electrode than at the other, causing unequal consumption. When using direct current, considerable energy is lost in the resistance which must be used to regulate the welding current. In alternating current this regulation is accomplished by reactance. This results in very little lost energy but has the usually unimportant disadvantage of a low power factor (approximately 0.3), unless corrected by the addition of capacitors. In the earlier models a constant potential transformer was used with an external reactor, while in a recent model, leakage reactance built into the transformer serves a similar purpose. Also, in this later model, capacitors have been used to improve the power factor through the major portion of the current range.

Alternating current has the disadvantage that when the frequency is lower than 40 cycles, it is difficult to maintain an arc and a frequency changer set is desirable.

Equipments generally are furnished reconnectable for 440 and 220 v., single phase power supply. However, transformers may be obtained for practically any supply voltage, either as separate units or with a special primary winding in the standard units. The control circuit usually is 110 v., while the welding circuit is provided with an open circuit voltage of 300 v. to insure ease in establishing and maintaining the arc.

MANUAL WELDING

Apparatus

The equipment for manual welding consists of a number of items which may be considered from the standpoint of whether their function is the control and direction of hydrogen or of electrical energy (see Figs. 1 and 2).

Hydrogen is commercially available in tanks or cylinders usually containing approximately 200 cu. ft. at a pressure of approximately 2000 psi. (The volume given is at atmospheric pressure.) If the quantity of gas used is sufficient to justify the capital investment, anhydrous ammonia

may be broken down into hydrogen and nitrogen by passing it through a suitable furnace, called an ammonia dissociator. Hydrogen gas obtained in this manner is satisfactory for welding and can be produced for approximately one-half the cost of hydrogen in cylinders, including an allowance for a somewhat higher rate of consumption. If special tips for this gas have not been obtained, the hydrogen tips should be changed so that the area of the orifice is 25% greater.

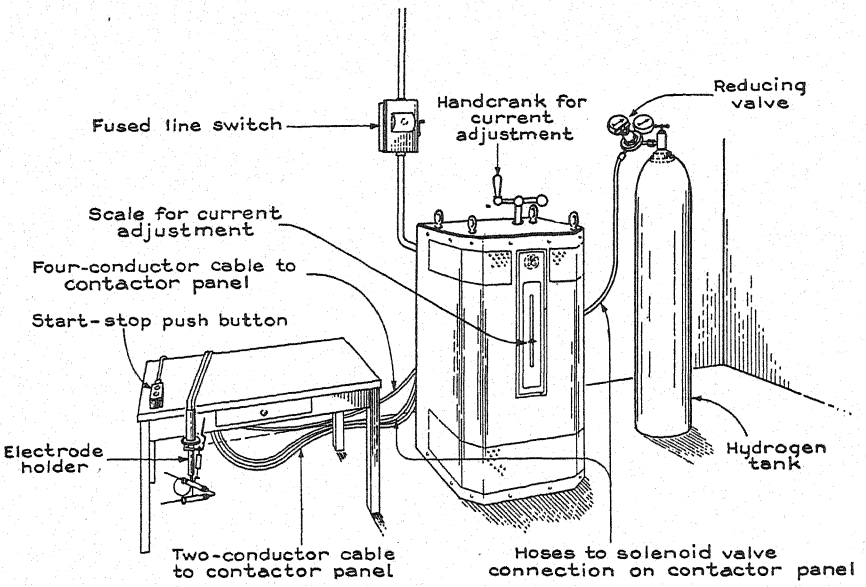


Fig. 1—Equipment for Manual Welding

The pressure of the source of hydrogen is usually higher than that required for welding. For this reason, as well as to insure a fairly constant welding pressure, a reducing valve is inserted in the line, usually attached to the hydrogen tank. This valve should have a high-pressure gage with a scale to suit the supply and for the low-pressure gage a scale of 0–50 psi. is recommended.

In the majority of cases, the equipment includes a solenoid operated valve, which opens to allow the flow of hydrogen when the electrical circuit is energized, and closes, when it is de-energized.

The electrical circuit requires a means of insulating the welding circuit from the supply circuit and for providing the necessary open circuit voltage for the former, a reactance or other means of varying the value of the welding current over a suitable range as required, and a system of contactors to provide ease in establishing and maintaining the arc and to minimize the possibility of shock to the operator.

The methods of providing for these functions differ in detail, but follow the same general scheme. The primary of the transformer is connected to the power supply through a fused line switch. The secondary is connected to the welding circuit through a contactor which is held closed

while the welding current is flowing but opens if the arc is broken. The welding circuit consists of an ammeter, the electrode holder and a variable reactance which may be included in the transformer as leakage reactance.

When the welding current is low, ease in starting is obtained by increasing the current during the starting period. This has been accomplished in a number of ways, all of which are utilized in equipments now in service.

In one equipment, a section of the reactor core is pivoted so that the reluctance of the magnetic circuit can be changed to vary the welding current. Normally, this section is held in the position of highest current by a spring, being rotated by the effect of the welding current to a position of lesser value, as determined by the movable stop which is set by the operator at the desired value. A dashpot prevents immediate rotation of the core to its final position, and thus provides for the higher current necessary in starting. The current adjustment is made by rotating a handle or lever to various stops arranged within an angle of about 90°. At the extreme left the current is about 15 amp., increasing to about 70 amp. as the handle is moved to the right.

In another equipment, the reactor has a fixed core, the current being varied by changing taps on the winding. During the starting period, a resistance is paralleled with the variable section of the winding to provide approximately uniform values for the starting current. After the arc is established, the resistance is disconnected and the current drops to the selected value. A plug and socket arrangement is used for changing taps. With the 15–70-amp. equipment, a current of about 15 amp. is obtained with the plug in the extreme left socket facing the panel, progressing in steps of about 5 amp. across the panel to 70 amp. at the extreme right. With the 60–150-amp. equipment, a current of about 60 amp. is obtained at the extreme left, progressing in steps of about 8 amp. to 150 amp. at the extreme right.

In a later equipment, the reactor is provided with a movable core, the position of which in respect to its coil determines the value of the welding current. An auxiliary coil, properly located with respect to the movable core and suitably connected through another reactor, increases the current during the starting period. The relative location of the auxiliary coil and the movable core is such as to provide approximately uniform values for the starting current. The core is moved to the desired position by the rotation of a handwheel. When changing the current, the arc should be established and the wheel rotated in the proper direction while the current is observed on the ammeter.

In the latest type of equipment, the reactance is incorporated in the design of the transformer as leakage reactance. The transformer is provided with a fixed core but with a movable primary and a fixed secondary coil, so that the relative location of the primary and secondary windings determines the value of the welding current. A tertiary winding, connected into the circuit during the starting period, provides for the increase in the current during the starting period. As in the previous case, current adjustment is made by rotating a handwheel. This moves the coil to the desired position which is indicated by a pointer moving on a vertical scale, the latter being calibrated in amperes so that current adjustment may be made either with or without the arc being established.

The electrode holder not only provides a means for establishing and maintaining the arc but also provides the stream of hydrogen with which the arc is enveloped (see Fig. 2). It consists of two tubes molded

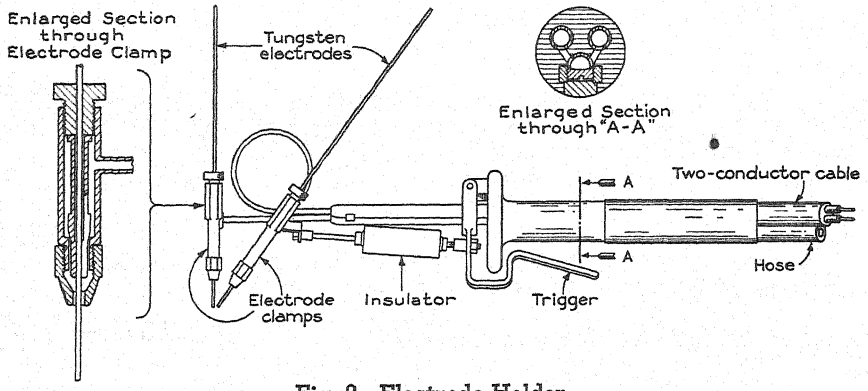


Fig. 2—Electrode Holder

in a composition handle through which both hydrogen and current flow. The current connection is made to these tubes at the rear of the handle, and is connected to the power control unit through a 2-conductor flexible cable. The hydrogen is supplied through a hose to a single tube at the rear of the holder from which it is led into the two current-carrying tubes by means of an insulated manifold in the molded handle. Both hydrogen and current are carried to the forward end of the electrode holder on which are mounted the electrode clamps. One of the electrode clamps is movable but is held in approximate position by a coil in the tubing and manipulation is through an insulated connection to the trigger. The coiled tube should be kept from the heat as much as possible to prevent annealing and destruction of its spring action.

The electrode holder is usually furnished in one of three ratings, 50, 75 or 100 amp. The 50-amp. size may be equipped with interchangeable clamps and tips for use with either 0.040-in., $^1/_{16}$-in. or $^3/_{32}$-in. diameter electrodes. The 75-amp. size may be similarly equipped for either $^3/_{32}$-in. or $^1/_8$-in. electrodes and the 100-amp. size for either $^1/_8$-in. or $^5/_{32}$-in. electrodes.

Selection of the electrode size is made according to the welding current used. Each size of electrode should be used with the electrode holder

Table 1—Current Range and Electrode Extension

Electrode diameter, in.	0.040	$^1/_{16}$	$^3/_{32}$	$^1/_8$	$^5/_{32}$
Current range, amp.	15–25	15–35	15–50	25–75	60–150
Maximum extension, in.	$^3/_4$	$^7/_8$	$^7/_8$	$1^1/_8$	$1^1/_8$
Minimum extension, in.	$^3/_8$	$^1/_2$	$^1/_2$	$^5/_8$	$^5/_8$

NOTE: Electrode extension is measured from the lower face of the hydrogen tip to the arcing end of the electrode.

equipped with the proper electrode clamp (see Table 1).

The line switch and fuse sizes are given in Table 2.

Operation

The method of current adjustment has been described in a previous paragraph for each of several types of equipment now in general use. This adjustment should be made to provide the proper welding current as dictated by the particular application (Table 3).

The electrodes should be adjusted to the maximum extension given in Table 1 before starting to weld. They are slowly consumed during welding and should be readjusted when they have reached the minimum extension. After the electrodes have been inserted, the clamp should be tightened only enough to hold them snugly. This allows adjustment of the electrodes by tapping lightly with a wooden or fiber block.

The angle between the electrode clamps should be such that, with the trigger free, the electrodes will be in contact when extending $^1/_8$ in. less than the minimum values given in Table 1.

Table 2—Line Switch and Fuse Sizes
Atomic Hydrogen Welding Equipment

Maximum Amp. Welding Current	Switch Rating 110 Volts	220 Volts	440 Volts	550 Volts
35	125 amp.	60 amp.	30 amp.	25 amp.
75	225 amp.	120 amp.	60 amp.	50 amp.
150	450 amp.	220 amp.	120 amp.	100 amp.

Table 3—Welding Current for Various Types of Welds
Atomic Hydrogen Manual Welding

Plate Thickness	Type of Weld Lap and Fillet	Butt	Corner	Edge
$^1/_{32}$	15–20	15–20	15–20	20–25
$^1/_{16}$	20–25	25–30	25–30	30–35
$^1/_8$	30–35	35–40	35–40	40–45
$^3/_{16}$	35–40	40–45	45–50	50–55
$^1/_4$	45–50	50–55	55–60	60–65
$^3/_8$	55–60	55–60	60–65	60–65
$^1/_2$	70–75	70–75	70–75	70–75

The travel of the movable electrode can be adjusted by means of the insulated turnbuckle connecting it with the trigger. This adjustment should be such that with the trigger free and the electrodes extending $^1/_8$ in. less than the minimum distance (see Table 1) they will touch. With the trigger pressed against the handle and the electrodes extending the maximum distance, they should be open about $^3/_8$ in.

The adjustment of hydrogen flow should receive careful consideration. A poor adjustment affects the welding speed or quality and causes either excessive hydrogen consumption or excessive tungsten consumption. Having selected the proper electrode holder and electrodes, set the cur-

rent for the highest value to be used with the electrode size selected (see Table 1). With the hydrogen reducing valve set at about 10 psi., strike and maintain the arc as described below. Reduce the pressure until small beads, indicating insufficient cooling and rapid tungsten loss, begin to form on the ends of the electrodes and the well-defined arc disappears. Increase the pressure until this condition is replaced by one in which the beads no longer form and a well-defined arc has appeared. Observe this gage reading which will be between 4 and 7 psi. and keep the reducing valve set at this point unless the electrode holder is changed. A different electrode holder, of the same or a different size, may require a different setting.

Reducing valves vary as to the minimum point at which they will hold pressure accurately. That required by the electrode holder is slightly less than 1 psi., but the throttling action of the solenoid valve may be adjusted so that the reducing valve will operate in its range of accuracy. There is an adjusting screw for this purpose on the solenoid valve which may not be accessible until the outlet connection is removed, but usually is accessible through a hole in the supporting panel between the inlet and outlet connections.

To start the arc set the reducing valve at about 10 psi., unless the hydrogen adjustment has already been made. Grasp the electrode holder and pull on the trigger until the electrodes are separated. Hold the start button depressed and allow the electrodes to come together and then immediately separate them about $^1/_{16}$ in. This ignites the hydrogen and starts the arc. If the arc is not started the first time, close and open the electrodes again. The start button should be released as soon as the arc is started. Then adjust the flow of hydrogen as described above. If the electrodes freeze together, depress the stop button and gently force the electrodes apart with filler rod or pliers, and proceed as before. The electrodes are brittle, and care should be exercised to avoid breakage. Another frequently used method to establish the arc is to separate the electrodes slightly after the hydrogen is ignited and draw them across a piece of charred wood, graphite or steel.

To stop the arc, depress the stop button or increase the gap between the electrodes until the arc breaks. While the arc may be "snuffed out" by bringing the electrodes together, it is poor practice and should be avoided. If this should occur, intentionally or otherwise, the electrodes should be separated by depressing the trigger, or the stop button should be depressed to remove power from the welding circuit, and the electrodes pried apart.

The use of filler rod depends on the desired finished appearance, and thickness and type of work being done. In the case of butt welds where the thickness exceeds $^3/_{16}$ in., it is necessary to bevel the edges in order to obtain uniform and complete penetration and to add filler rod to supply the metal to fill the groove. All fillet welds require filler rod, and it is frequently required in the other types of welds.

Safety Note.—In all of the equipments furnished commercially the electrical circuits have been arranged to reduce to a minimum the possibility of shock, a danger inherent in all electrical apparatus. In establishing the arc the electrode holder normally is held in one hand with the other engaged in depressing the START button, thus avoiding contact with the exposed

parts of the electrode holder during the time the open circuit voltage is available. The arc is stopped either by depressing the STOP button or by separating the electrodes until the arc will no longer sustain itself and breaks, causing the control circuit to remove power from the electrode holder. As stated previously the arc should not be "snuffed out" by allowing the electrodes to come into contact unless the STOP button is immediately depressed.

Technique

Welding technique is primarily craftsmanship and, while certain fundamentals may be laid down as a basis, like craftsmanship in any line, its acquisition rests ultimately with the individual. With a few hours of practice, an operator can learn how to start the equipment and to make the necessary adjustments of welding current and hydrogen flow. With this knowledge and a few simple rules he can make satisfactory welds on plate stock. Skill in the welding of complex sections, the repair of molds and dies and similar problems must be acquired by experience or from a competent instructor.

The factors which constitute welding technique are grouped naturally into two classes: adjustments of the equipment and manipulation. These factors are interrelated, and as the operator's skill in manipulation increases, a change in the equipment adjustments is perfectly logical, and for this reason strict adherence to the current adjustments given in the following is not recommended.

Familiarity with other methods of welding is of some assistance to the operator who is just learning to weld with the atomic hydrogen process. Steadiness of hand and accuracy of touch are requirements common to all processes and will be of assistance as will the general knowledge of counteracting warpage. But the student's first problem is to acquaint himself with the manipulation of the electrode holder when using various welding currents, and then to learn how this can best be applied to the problem at hand.

As the work does not form a part of the electrical circuit, the arc may be started with the electrode holder in any position. The majority of experienced welders start the arc with the electrode holder in a vertical position and raised slightly above the head. This allows the operator's helmet to be in the raised position until ready to start actual welding.

The distance between the tips of the electrodes determines the arc voltage and the type and size of the arc stream. In normal use, the arc stream or flame assumes a fan shape which varies in diameter between $^3/_8$ in. and $^3/_4$ in. Under these conditions the arc voltage varies between 50 v. and 90 v., and the arc produces a singing noise. If the electrodes are brought closer together so as to reduce the diameter of the fan below $^3/_8$ in. the singing noise stops and the fan suddenly disappears, being replaced by a pointed arc extending about $^1/_{16}$ in. beyond the tips of the electrodes, usually called a "silent" arc. In this case the voltage ranges between 20 v. and 40 v.

When the arc stream is viewed through a welding glass, it is seen as a very definite circular outline having very little depth and normally lying

in a plane substantially the same as that of the electrodes. This is the normal position, that is, the electrodes lie in exactly the same plane (see Fig. 3 (*a*)). However, the electrodes can be offset to rotate the fan to a position approximately at right angles to the plane of the electrodes. In this position the electrodes lie in two parallel, but slightly displaced, planes (see Fig. 3 (*b*)). While an adjustment is provided for this purpose on the automatic head, no such means is provided on the electrode holder. If it is desired to permanently displace the fan to the right angle position, the spring loop may be gently forced into the desired position, but frequent changes of this nature are not recommended and may result in permanent injury or destruction of the electrode holder.

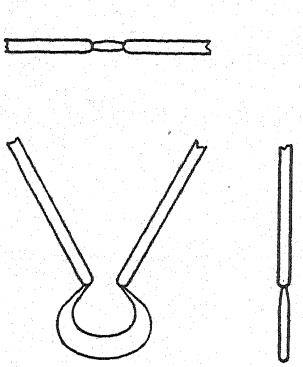


Fig. 3 (*a*)

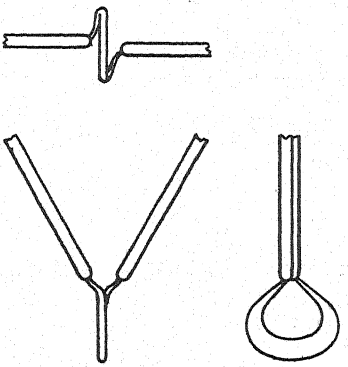


Fig. 3 (*b*)

Types of Flame

The greatest concentration of atomic hydrogen occurs at the outer boundary or fringe, and this edge should just touch the surface to be welded. Carrying the arc higher than this spreads the heat over a larger area and is useful for preheating or for finishing off the end of the weld. If the arc is too low, heat is inefficiently distributed and the electrodes will be contaminated unnecessarily by spatter from the weld which lowers their melting point, and causes excessive consumption.

Spatter will accumulate on the tungsten electrodes and on the tips through which hydrogen gas flows. That which adheres to the electrodes will later alloy with the tungsten and that which adheres to the tips will cause poor gas distribution. A wire brush is effective in removing a lightly adhering spatter, and if used frequently will usually be all that is required. A dull edged tool such as a screw driver or file prong may be used to remove tightly adhering spatter. Failure to remove this spatter will result in excessive tungsten consumption and may influence adversely the speed and quality of welding.

Filler rod is added by creating a liquid surface or molten pool, depending on the penetration required, and adding drops of the melted filler rod to it, fusing thoroughly, but quickly. As a general rule, it is better to melt the end of the filler rod by intermittently inserting it in the forward fringe of the fan. The added metal is fused as the flame moves forward to continue the weld.

Care must be taken to prevent contamination of the tungsten electrodes by allowing the filler rod to touch them. The alloy thus formed has a lower melting point than tungsten, and a molten ball usually forms on the end of the electrode causing the arc to be very erratic. The disturbing alloy will disappear if the arc is maintained for a sufficient length of time but may be quickly removed by rapidly moving the electrode holder up and down with the arc established. This causes the hydrogen to be temporarily displaced, allowing the air to oxidize the alloy very quickly. Another practice is to stop the arc and break off the disturbing alloy with pliers.

The nature of the work governs the selection of the welding current, and the size of the fan-shaped flame. For thin metals and small parts the lower currents are used with a small fan or a "silent" arc. Both the current and size of the fan are increased as the size of the work increases.

The amount of heat available for welding depends both on the welding current and the size of the fan-shaped flame. The welding current is selected before the weld is started, but the size of the fan and its distance from the weld surface may be varied during welding to obtain different degrees of heat. The operator must learn to keep the fan uniform except where conditions warrant a change. When finishing a weld it is desirable to reduce the heat by drawing the fan away from the molten pool slowly. This reduces the tendency to form a crater or to leave a porous spot, as its purpose is to prolong the molten condition of the surface, thus allowing gases, which might otherwise be trapped, to escape as solidification progresses upward. At times it may be necessary to employ the "silent" arc to effect a similar result. A similar technique may be followed at any point in the welding where difficulties arise due to inaccurate spacing or improper manipulation.

Under the atomic hydrogen flame the molten pool is extremely fluid and must be fully confined to prevent movement under gravitational force. Such confinement by a means foreign to the welding problem itself usually is not practicable. In very unusual cases, dams of copper, refractory material or graphite may serve the purpose. Of these, graphite is to be preferred as it does not have the rapid chilling effect of copper nor does it disintegrate as rapidly as bonded refractory materials.

The most satisfactory solution is to confine the molten pool in a vessel or pocket formed by the adjacent solid metal, aided by the surface tension of the liquid metal. It is obvious that if complete penetration is to be secured, the bottom of this vessel cannot remain unmelted. If not too deep, the molten pool may be sustained by the surface tension of its bottom surface. The depth of the pool which can be thus sustained is about $^{3}/_{16}$ in. and, in the case of butt welds, determines the maximum thickness which can be welded with complete penetration without beveling or without sustaining the pool by some sort of artificial backing. In the latter case porosity or contamination of the weld metal is likely to occur. In the former case, beveling should be such as to leave a rootface not exceeding $^{1}/_{8}$ in. and welding may be done in two or more passes or in a single pass by manipulating the flame so that the rootface is welded and solidified before it is called on to support the weight of the added metal. Filler rod is added to fill the groove and to build any reinforcing bead.

Though frequently impracticable, it is always desirable to bathe the underside of the weld with hydrogen during the period in which oxidizing temperatures prevail. This is particularly true of stainless steels and other alloys containing a constituent which otherwise would cause a thick crust of oxide to form, reducing effective penetration and the efficacy of the surface tension in supporting the liquid metal above. One method of accomplishing this is to provide a welding fixture containing a groove spanning the weld zone, and wide and deep enough to avoid contact with the liquid metal (see Fig. 4). Hydrogen fed to this groove at a very low pressure will prevent oxidation and in many cases will reduce oxides already present.

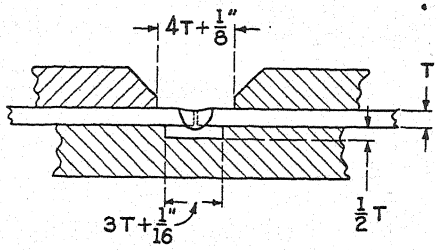


Fig. 4—Method of Supplying Hydrogen to Underside of Weld

In the selection of welding current, consideration must be given to the requirements of the weld and to the experience or ability of the operator. If the weld is long and the parts not very securely held, or the finished appearance exacting, lower current values must be used. Also, higher currents are permissible as the experience and ability of the operator increase. Table 3 is a guide to the selection of the proper values.

While the greatest concentration of heat on the seam occurs when the fan is vertical and in line with the seam, better heat distribution in the metal adjoining the weld is obtained with the fan at an angle to the seam. This angle varies from practically zero for material less than $1/16$ in. thick to about 30° for material over $3/8$ in. thick. To increase the ease of manipulation when filler rod is to be added, the fan is frequently inclined slightly from the vertical and away from the side from which the filler rod will be inserted.

To a large extent, the manipulation of the electrode holder is the same for the many types of welds encountered. At the beginning of a weld a small area should be preheated. This requires a very short time as its purpose is to approximate the heat distribution ahead of the arc which is present after the weld has progressed a short distance.

When making a butt weld, penetration is determined by observing the width of the bead and the action of the molten pool. When the surface of the weld first becomes molten the pool is very active. As the heat penetrates into the metal the activity slows down until the surface is almost quiet. This condition combined with a bead width of about three times the plate thickness indicates complete penetration. With edge welds the

fan is carried more nearly parallel to the seam and inclined very little from the vertical, and penetration is satisfactory when the molten pool flows to the outer edges of the plates and is well rounded. Penetration of corner welds and lap welds are judged entirely by the action of the molten metal.

In the case of lap welds, the heat is applied mostly to the lower plate allowing just enough on the top plate to cause it to flow into the molten pool. Filler rod, if used, should be added so that it flows from the upper to the lower plate. Air space between the plates should be kept at a minimum to facilitate the flow of metal to the lower plate. Such an air space is aggravated with the application of heat and with thin materials will cause a ragged appearance of the weld.

The making of fillet welds is very similar to that of lap welds, the principal differences being that filler rod is always used and the proportion of heat applied to the upper or vertical plate is greater.

The welding of alloy steels offers a problem which is only slightly different from that of mild steel. A lower welding current is usual, particularly in the case of steels that are high in the percentage of alloying material, such as stainless steel. The analysis of the filler rod, when used, should be practically the same as the parent material except for carbon content which should be about one-third greater. The carbon loss during welding, for which this increase in the carbon content of the filler rod is to compensate, is dependent on the length of time the metal is molten. Obviously, the metal must be molten for a longer time on heavier sections and the filler rod should be high in carbon content if the weld metal is to have the same analysis as the parent metal. The loss of other alloying ingredients usually is negligible.

A frequent problem is the addition of small amounts of filler metal to a comparatively large mass as exemplified in the repair of molds and dies. In most instances, alloy steels are involved, and the selection of filler rod is important. The increase in carbon content follows the principles outlined above noting that the amount of filler added may be a considerable portion of the melted metal, and the length of time the metal is molten depends largely on the job to be done. The distribution of heat is also important, particularly throughout the metal adjacent to the weld. Preheating is of assistance and is recommended on all but the very small pieces weighing 2 lb. or less. Even these should be heated until they are hardly comfortable to the touch before welding is begun. The amount of preheating increases with the size so that a piece weighing 50 lb. or more would be heated to a dull red temperature. To further assist the heat distribution, the metal should be brought to the melting point slowly, and when the surface is molten, the filler should be added. If the melting point is reached quickly, proper manipulation must insure slow cooling in order to avoid porosity, which usually is the result of rapid cooling.

The atomic hydrogen process is applicable to practically all the nonferrous metals and alloys. With the exception of aluminum and copper and their alloys, flux is rarely required. Flux for either of these groups is readily obtainable and selection is largely a matter of individual choice. As a general rule all such metals and alloys should be preheated and lower values of welding current used than with similar masses of steel. Otherwise, the technique is the same as that previously outlined.

AUTOMATIC WELDING

Apparatus

The equipment for automatic welding, sometimes called machine welding, includes a welding fixture in addition to the units previously described for manual welding. Also, the electrode holder is replaced by a welding head and an arc control panel for maintaining the length, or size, of the arc at a uniform value.

The actual form of the welding fixture will depend entirely on the work to be done. Briefly, it will provide for clamping and holding the work in position and for moving the arc along the seam or for moving the work under the arc. Uniformity of all welding conditions, including alignment and fit of the seam, determine largely the success of automatic welding. These points should be particularly stressed in the design of the welding fixture as any compromise is likely to result in lower welding speeds, a higher percentage of rejects or both.

The welding head is arranged for mounting on the welding fixture and, if not provided with vertical and cross-seam adjustments, these must be included in the welding fixture. A motor, operating through a gear train, drives the electrodes in one direction or the other as required to maintain a constant arc voltage. Hydrogen is fed to a nozzle which causes it to be properly distributed around the electrodes. Portions of the head subjected to the heat of the arc are water cooled. An adjustment is provided for offsetting the electrodes so as to stabilize the arc. With the proper offset the magnetic effect of the welding current causes the plane of the fan-shaped flame to rotate to a position approximately at right angles to the plane of the electrodes (see Fig. 3 (*b*)). If this offset adjustment is incorrect the fan may oscillate between this position and that normally assumed in manual welding, resulting in non-uniform penetration.

When a greater production rate is required than can be obtained by a single arc, additional units may be installed, or the required number of arcs may be incorporated in a single welding head. While the number of installations of multiple-arc units are few and the experience necessarily limited, it may be stated generally that this method has the advantages of broadening the field of application to include heavier material and of lowering the cost per unit length of weld. The improvement in cost is largely due to lower rates of consumption per arc of both hydrogen and of tungsten.

The function of the arc control panel is to furnish impulses to the electrode driving motor causing it to move the electrodes so as to establish and maintain the arc at a uniform, predetermined voltage. The principal unit in this panel is the voltage-sensitive device which furnishes the impulses to the electrode motor. This may consist of a voltage relay, the coil of which, in series with a regulating rheostat, is connected to the electrode terminals. Recently, thyratron tubes have been used to perform this function. Such a control system is responsive to very small changes in arc voltage and can be arranged to furnish feeding speeds proportional to the variation of the arc voltage from normal. The result is that the arc voltage can be held within much closer limits than with a system which contains moving mechanical parts.

Table 4—Welding Speed
Atomic Hydrogen Manual Welding

Plate Thickness or Welding Current	Welding Speed in In. per Min.			
	Lap and Fillet	Butt	Corner	Edge
1/32	....	8–9	11–12	11–13
1/16	8–9	9–12	13–14	12–13
3/32	7 1/2–8 1/2	8–10	10–11	10–12
1/8	7–8	7–10	9 1/2–10	9–10
5/32	5–6	5–7	6 1/2–8	7 1/2–9
3/16	3 1/2–4 1/2	3–3 1/2	4–5	5 1/2–6
1/4	2 1/2–3 1/2	2 1/2–3	3–3 1/2	4–4 1/2
5/16	2–3	1 1/2–2 1/2	2 1/2–3	3–4
3/8	2–2 1/2	1–1 1/2	2–3	2 1/2–3 1/2
1/2	1 1/2–2	3/4–1	1 1/2–2	2–2 1/2
100 amp.		6–9 cu. in. per hr. deposited metal		
125 amp.		7–8 cu. in. per hr. deposited metal		
150 amp.		8–10 cu. in. per hr. deposited metal		

Table 5—Hydrogen and Tungsten Consumption
Atomic Hydrogen Manual Welding

Welding Current, Amp.	Power Consumption, Kw.	0.040 Electrodes		1/16-In. Electrodes		3/32-In. Electrodes		1/8-In. Electrodes		5/32-In. Electrodes	
		Hydrogen, Cu. Ft. per Hr.	Tungsten, In. per Hr.	Hydrogen, Cu. Ft. per Hr.	Tungsten, In. per Hr.	Hydrogen, Cu. Ft. per Hr.	Tungsten, In. per Hr.	Hydrogen, Cu. Ft. per Hr.	Tungsten, In. per Hr.	Hydrogen, Cu. Ft. per Hr.	Tungsten, In. per Hr.
15	0.90	30	1.10	40	0.83						
20	1.24	30	1.80	40	1.35						
25	1.60	30	2.75	40	2.10						
30	1.98			40	3.08	45	1.33	55	0.80		
35	2.38			40	4.30	45	1.67	55	0.97		
40	2.80			40	5.75	45	2.08	55	1.12		
45	3.24					45	2.57	55	1.32		
50	3.70					45	3.12	55	1.53		
55	4.17					45	3.75	55	1.75		
60	4.68					45	4.40	55	2.00		
65	5.20							55	2.28		
70	5.73							55	2.60	90	2.40
75	6.32							55	2.93	90	2.60
80	6.87							55	3.30	90	2.90
90	7.92							55	4.23	90	3.45
100	9.02									90	4.10
110	10.12									90	4.75
120	11.26									90	5.55
130	12.45									90	6.45
140	13.70									90	7.65
150	15.05									90	9.20

The arrangement and location of units for automatic welding depends largely on the space available and the variety of jobs to be welded. It is desirable to locate the power control unit near the welding fixture as this eliminates unnecessary power loss in the leads and is convenient to the operator when the welding current must be changed frequently.

Technique

Automatic welding is limited almost entirely to comparatively long straight seams in formed plate and to seams having a contour which can be followed readily by automatic displacement of the welding head. The uniformity of conditions provided by automatic control makes possible the use of higher values of welding current with a resulting increase in the welding speed. Fullest advantage of these possibilities can be realized only when a uniform seam is presented to the arc.

The technique follows the same principles outlined for manual welding. As a rule, adjustments are determined by welding sample sections and are not changed during welding. The arc voltage, being automatically controlled, determines the size of the fan-shaped flame which remains constant for the length of the weld. The welding fixture is designed to hold constant the height of the arc above the work. These two factors are interrelated, as a decrease in the size of the fan raises the fringe and has the equivalent effect of raising the head.

The angle between the seam and the fan-shaped flame is determined by the mounting of the welding head, which, as a rule, is such as to make the fan and the seam parallel. This may be altered slightly by a change in the offset adjustment, the primary purpose of which is to stabilize the position of the fan at various values of welding current.

WELDING DATA

The over-all welding time, as the term is generally used, includes the time necessary to set up the parts for the welding operation, as well as the time consumed in welding. The former varies over a wide range and depends not only on the variety of work being welded but on the design of the parts, preceding workmanship and the facilities available for making a proper set-up. For cost purposes it is frequently computed as a percentage of the welding time. In the data given below this is not included, welding speeds being based on the time necessary to make the weld, usually called "arc time."

The manual welding speeds are given in Table 4. In using these data for computing welding time, the length of the seam should be increased to compensate for the time required to start and finish the weld and for intermediate pauses. A fairly accurate value is 1 in. plus an additional inch for each 2 ft. of length.

For computing cost, these data must be used in conjunction with Table 3, which gives the welding current required, and Table 5, which gives the consumption of hydrogen, tungsten and power for various current values. For instance, a butt weld, 12 in. long on $^1/_8$-in. plate, should be made at a

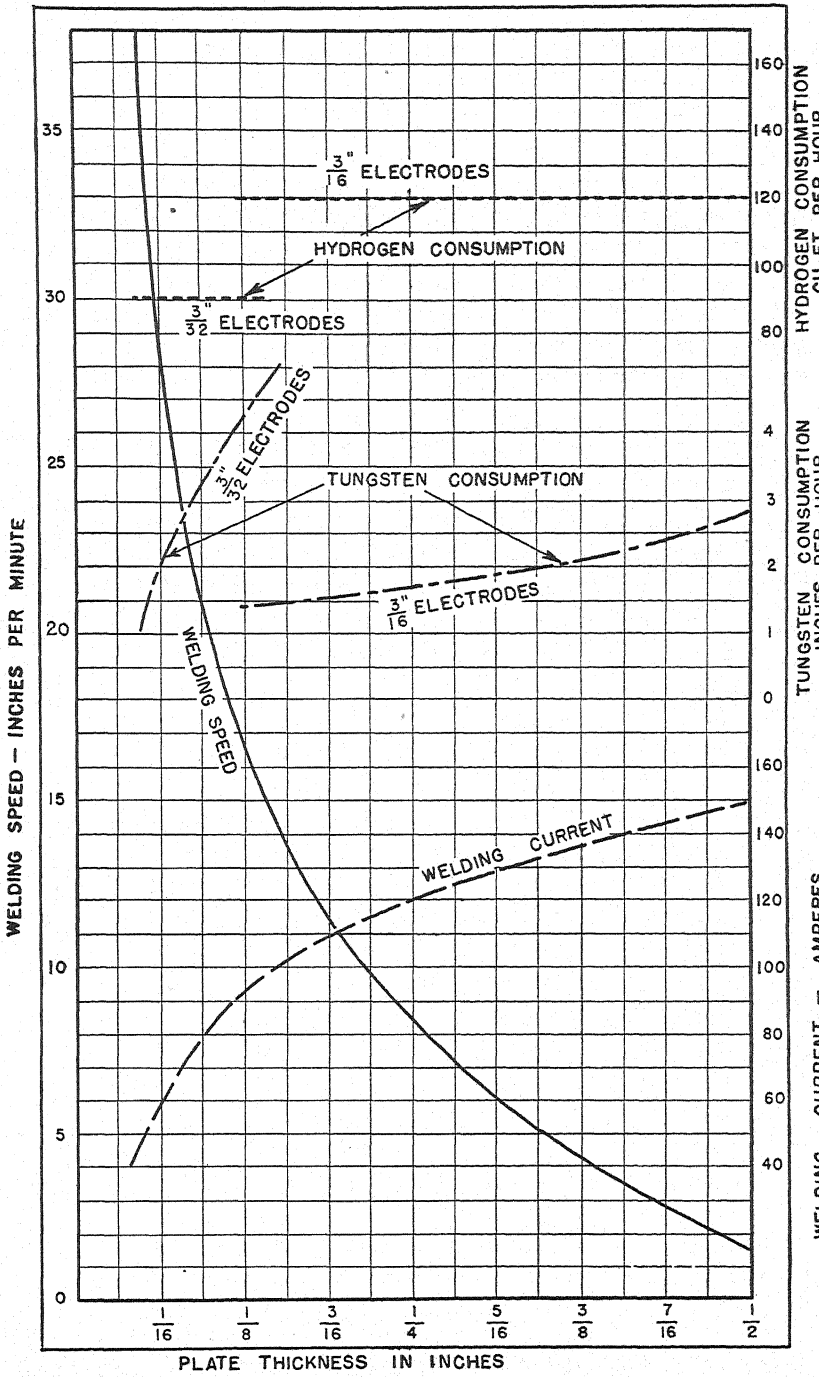

WELDING SPEED — INCHES PER MINUTE
HYDROGEN CONSUMPTION CU. FT. PER HOUR
TUNGSTEN CONSUMPTION INCHES PER HOUR
WELDING CURRENT — AMPERES
PLATE THICKNESS IN INCHES
3/16" ELECTRODES
HYDROGEN CONSUMPTION
3/32" ELECTRODES
3/32" ELECTRODES
TUNGSTEN CONSUMPTION
3/16" ELECTRODES
WELDING SPEED
WELDING CURRENT
0
5
10
15
20
25
30
35
40
60
80
100
120
140
160
0
1
2
3
4
1/16
1/8
3/16
1/4
5/16
3/8
7/16
1/2

Fig. 5

speed of 7 in. per minute (Table 4) or in 1.86 min. ($^1/_7 = 1.86$) and the current required is 35 amp. (Table 3). From Table 5 either $^1/_8$-in. or $^3/_{32}$-in. electrodes may be used, and, if the latter, the hydrogen consumption is 45 cu. ft. per hr., the tungsten consumption is 1.67 in. per hr. and power consumption 2.38 kw. From this and the cost of these items the operating cost per hr. may be computed and then the cost of making the weld.

For automatic or machine welding, the data given in Fig. 5 include welding speed and hydrogen, tungsten and power consumption. Computation of cost is made as described above, omitting the addition for the start and finish of the weld.

CHAPTER 7

SUBMERGED MELT WELDING*

Description of Process, Quality of Welds, Applications of Process, Equipment and Supplies Required, Type of Welds, Preheat and Post-Weld Requirements, Operator Requirements.

THIS electric welding process uses the heat generated by the passage of a heavy electric current between a bare welding rod and the work being welded. It differs from other electric welding methods, however, in many respects, and should not be confused with those processes generally classified as hand arc welding and automatic arc welding.

One of the outstanding characteristics of this type of welding is its automatic operation. The process provides not only mechanized welding but also other unique features which are of even greater importance than mechanization. This method provides the fastest metal deposition rate of any similarly applicable welding process. This is an important feature for welding all weights of metals from light gages to heavy thicknesses. Furthermore the method makes possible welding in one pass metals of thicknesses which require several passes by other welding methods. This capacity for speed in welding has established the economic practicability of this method of welding in many instances where mere mechanization would be uneconomical because of loss of portability and flexibility of the equipment, and the expense of installation.

The history of the development of this process is closely related to the interesting record of the development of methods of protecting deposited weld metal from the contaminating influence of the atmosphere. The need for such protection was recognized early in the progress of electric arc welding and the literature of the art is replete with references to numerous early investigations of the shielding of the weld deposit. Many and varied were the attempts to utilize some material which would afford effective shielding of the weld but for some time progress was slow.

The principal forms of shielding that were tried in an effort to exclude air from contact with the molten welding material were the gaseous envelope, a protective coating applied to the electrode and material laid in powder form along the welding joint. The method that first attracted wide attention was the coating of electrodes for metal arc welding and this

* The process described is generally known as the Unionmelt welding process. Prepared by a committee consisting of T. M. Jackson, Sun Shipbuilding & Dry Dock Co., *Chairman;* J. H. Hruska, Electro-Motive Corp.; J. M. Keir, The Linde Air Products Co.; R. M. Wallace, Griscom Russell Company.

so improved welding quality that metal arc welding could meet the most exacting requirements. The coated electrode was probably the most important factor influencing the world-wide adoption of welded construction by the metal working industry.

With this development came attempts to apply to these improved welding conditions some form of mechanization that might tend to reduce the dependence on the welding operator. However, the problem of introducing the welding current while continuously feeding the electrode was an outstanding difficulty in the mechanization of welding with coated electrodes. The simplicity of using bare wire electrodes in mechanized welding clearly indicated the desirability of introducing the protective material separately into the welding zone. Various compositions of powdered fluxes or protecting materials were developed and the methods of welding involved their separate introduction into the welding zone and became known as smothered arc welding. In these methods, however, the visible arc, often with considerable sparking and sputtering, remained a dominant characteristic. In fact, the use of somewhat higher currents than were practical in manual welding and the characteristics of some of the materials added to the welding zone often produced arc action of unusual vigor.

The methods of smothered or submerged arc welding did not obtain wide use. No one had given the process a thorough and comprehensive scientific study to the end of developing satisfactory fluxes and technique for different classes of work. A satisfactory mechanism for its application had never been thoroughly developed.

For the submerged melt welding process there have been developed satisfactory fluxes, excellent mechanical equipment, as well as knowledge of a successful technique. The extensive use of this process has proved of great practical value in saving of both time and labor, as well as in a definite improvement in quality for many types of work.

Description of Process

In this electric welding process there is no visible evidence of the passage of current between the welding rod and workpiece. The welding rod is not in actual contact with the workpiece, but the current is carried across the gap through a special granulated material. This material is a finely crushed mineral composition usually gray or greenish gray in color. It is a completely reacted, specially manufactured product, and even when brought to the high temperature of the welding zone it does not give off any appreciable quantities of gas and is practically unchanged chemically. A supply of this dry, finely-divided, free-flowing material is automatically laid down along the seam to be welded in sufficient depth to cover completely the end of the welding rod at all times during the actual welding operation. The entire welding action takes place beneath this granulated material without sparks, spatter, smoke or flash. No protective shields, goggles, helmets, smoke collectors or ventilating systems are needed. Figure 1 shows how a submerged melt butt weld is made.

The granulated material is the basic feature of this method of welding, making possible the special operating characteristics which distinguish the process. The material is a non-conductor of electricity when cold, but in the molten state it becomes a highly resistant conductive medium.

Before beginning a weld, therefore, it is necessary to provide an initial conductive path for the welding current. This is usually accomplished by placing a small wad of steel wool between the end of the welding rod and the workpiece, before the welding current is turned on. The heat instantaneously generated by the initial flow of current passing through the steel wool is sufficient to cause the lower portion of the granulated material surrounding the end of the rod to become molten, which permits the welding action to continue. The upper, visible portion of the granulated material is not melted, but remains unchanged in appearance and properties, and can be reused. When melted and maintained in a molten state during welding, the material provides exceptionally suitable conditions so that unusually high current densities can be used. Hence great quantities of intense heat are rapidly generated. However, due to the good heat-insu-

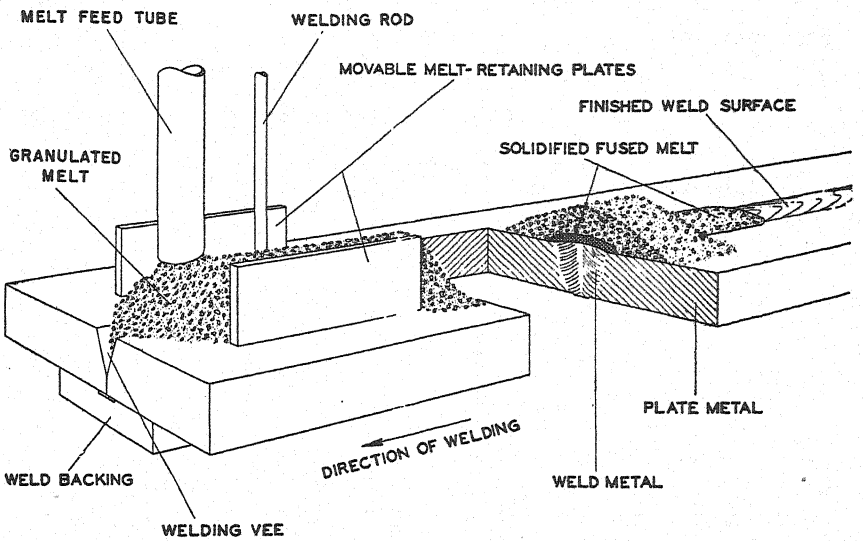


Fig. 1—This Sketch Shows How a Submerged Melt Butt Weld Is Made

lating capacity of the molten and granulated layers of material, this intense heat is concentrated in a relatively small welding zone where the welding rod and the base metal are rapidly fused, making possible high welding speeds. The large volumes of metal which are fused at one time make it necessary that welding be done in an approximately horizontal position so that the fluid materials will not flow out of the welding zone.

Unusually deep fusion into the base metal can be obtained by this concentrated, intense heat, and consequently a relatively small welding vee can be used, requiring correspondingly small additions of welding rod. As a rule, when welding by this method, nearly two volumes of base metal are fused for each volume of filler rod added. Under usual welding conditions, the quantity of granulated material which is melted in the lower portion of the applied layer weighs approximately the same as the welding rod which is added. The subsurface pool of this molten portion floats on

SUBMERGED MELT WELDING

Table 1—Section 1—Boiler Plate Steel for A.S.M.E. Code Boilers and Pressure Vessels

Type of Steel	Condition	Yield Point Psi.	Ultimate Strength Psi.	Elongation 2 In.	Reduction Area	Charpy Impact Ft-Lb.
Firebox S-1 A.S.T.M. A-70	Plate A.R.	27,500	55,000	28	..	..
0.505 all weld metal	A.W.	54,300	72,000	30	59	34
	S.R.	46,700	67,300	33.5	62	42
High-strength S-55 A.S.T.M. A-212	Plate A.R.	45,000	78,000	27	..	..
0.505 all weld metal	A.W.	53,000	80,000	22	32	14.5
	S.R.	38,000	71,700	32	61	26.5
Carbon-molybdenum firebox S-44 (0.5% Mo) A.S.T.M. 204-39T	Plate A.R.	43,000	75,000	23.4	..	..
0.505 all weld metal	A.W.	66,500	87,000	23	56.5	..
	S.R.	61,000	82,000	27.5	58	25.5

A.R.—As received.
A.W.—As-welded condition.
S.R.—Stress-relieved condition.
Endurance limit is about 50% of the ultimate strength of welds made in low-carbon steel or 30–35 thousand psi.
Charpy impact tests made at room temperature using keyhole notch.

top of the weld puddle and solidifies upon cooling to form a glass-like slag. However, none of this action is visible since it is covered by the unfused portion of the material. After the welding action is completed, this unfused, granulated portion is picked up, either manually or pneumatically, and reused. The solidified portion contracts as it cools, and either detaches itself or is easily removed from the weld surface.

In addition to making possible the use of high welding currents and concentrating the generated heat, this material also acts as a cleanser, absorbing impurities from the fused metal. Furthermore, by melting and floating over the molten weld metal, it protects the fused metals from atmospheric contamination. Consequently the weld metal is clean and dense, and has excellent physical properties.

Quality of Welds

The welds, made under a protective layer of granulated and molten material of special composition, washed by intimate contact with the overlying molten layer of material and allowed to solidify while still protected, can be expected to be of superior quality. The welds have unusual strength, ductility, shock resistance, uniformity, density, low nitrogen content and corrosion resistance. Physical properties are as good as, and often better than, those of the base metal, as can be seen from an examination of Table 1.

Table 1—Section 2—Carbon and Low Alloy Steels

Type of Steel	Condition	Yield Point Psi.	Ultimate Strength Psi.	Elongation 2 In.	Reduction Area	Charpy Impact Ft-Lb.
Man-Ten (3/4 in. thick)	Plate A.R.	51,500	92,000	23	44	36
	Plate S.R.	47,500	81,700	30.5	66	49
0.505 all weld metal	A.W.	79,000	96,000	25	51	27
	S.R.	61,500	84,000	29.5	62	34
Sil-Ten (3/4 in. thick)	Plate A.R.	43,500	83,000	28.5	52	21
	Plate S.R.	45,000	76,500	32	60	23.5
0.505 all weld metal	A.W.	68,500	92,500	22.5	42	25.5
	S.R.	54,000	81,000	30	62	29.5
Cor-Ten (3/4 in. thick)	Plate A.R.	44,000	69,500	35.0	62.1	31.5
	Plate S.R.	48,000	65,500	36.0	68.8	35.3
0.505 all weld metal	A.W.	58,500	81,500	23.0	50.8	21.5
	S.R.	51,000	75,000	27.5	61.1	21.8
Cromansil (Cr-Mn-Si alloy) S-28; A.S.T.M. 202—39T	Plate A.R.	45,000	75,000	21	..	...
0.505 all weld metal	A.W.	61,000	87,500	21.5	36	...
Silicon structural steel						
0.505 all weld metal	A.W.	55,200	97,200	17	22	15
Special Cr-Mo-2% Ni steel (3/4 in. thick)						
0.505 all weld metal	A.W.	69,000	104,000	21	48	18-32
	S.R.	71,000	92,000	24	59	27-43
Special low Cr-Cu steel (2 in thick)						
0.505 all weld metal	A.W.	..	...	..	..	18-28
	S.R.	54,000	80,000	27	61	30-37
Special Ni-Cr steel (S.A.E. 3435 approx.)						
0.505 all weld metal	A.W.	69,000	97,000	21.5	33	12
Voloy	A.R.	61,000	91,000	26.5	..	21-29
0.20% C grade	S.R.	61,000	91,000	26.5	..	21-29
0.505 all weld metal	A.W.	68,000	93,000	21.5	..	14-17
	S.R.	62,000	84,000	27.0	..	26-32
Manganese vanadium steel (1 1/4 in. thick)	Plate A.R.	53,270	80,480	33.5	64.2	...
	Plate S.R.	56,000	81,000	29	61	...
0.505 all weld metal	A.W.	69,600	85,700	26	56	...
	S.R.	63,900	82,700	26	58	...
High carbon steel (0.45C, 1.25Mn) (1/2 in. thick)	Plate A.R.	67,000	118,200	16	..	...
Transverse specimen	A.W.	..	103,500	25	..	...
	S.R.	..	89,600	36	..	...
Mayari (5/8 in. thick)	Plate A.R.	51,400	73,600	26 in 8 inches		
0.505 all weld metal	A.W.	67,000	91,800	24 in 1 1/2"	49.7	20
	S.R.	63,400	83,600	25.3 in 1 1/2"	57.3	27

Charpy impact tests made at room temperature using keyhole notch.

Table 1—Section 3—Chrome and Chrome-Nickel Corrosion-Resistant Steels

Type of Steel	Condition	Yield Point Psi.	Ultimate Strength Psi.	Elongation 2 In.	Reduction Area	Charpy Impact Ft-Lb.
18–8 Cr-Ni stainless columbium-bearing, A.S.-T.M.A-167—35T	Plate A.R.	30,000	80,000	40	..	....
0.505 all weld metal	A.W.	40,000	76,500	53	57	56 (Izod)
4–6% Chrome 0.5 molybdenum steel	Plate A.R.	...	...	..	..	70
0.505 all weld metal	A.W.	111,000	166,000	7.3	16	16–65
	Annealed	50,700	78,000	32	69	44–82
Columbium treated 4–6% Cr 0.50 Mo steel	Plate A.R.	34,000	63,000	38	81	80
	Annealed	28,000	62,000	39	78	81
0.505 all weld metal ($^7/_8$ in. plate)	A.W.	129,000	157,000	2	2	6
	Annealed	36,000	70,000	33	69	45
14–16 Chrome steel A.S.T.M. A-176—38T	Plate A.R.	35,000	70,000	25	..	....
0.505 all weld metal	S.R.	...	76,800	27	..	....

Charpy impact tests made at room temperature using keyhole notch.

Welds made by this process have met the rigid requirements of the A.S.M.E. code for power boilers and for Paragraph U-68 pressure vessels, and have been accepted by various insurance and inspection companies. They have been approved for many ship-welding applications by the American Bureau of Shipping, by the Bureau of Marine Inspection and Navigation of the Department of Commerce, by Lloyd's Register of Shipping and by the United States Navy.

Uniformly high quality welds require good quality homogeneous base material if maximum welding efficiency is desired. Some sacrifices in welding speed and efficiency must be made when welding less homogeneous plate material containing slag or otherwise not perfect.

Weld Structure

Macro-etched cross-sections of one-pass welds made by the submerged melt process reveal a distinct dendritic structure which has sometimes been misinterpreted. Dendritic structure in welds produced by other methods has sometimes been found undesirable, and it is quite natural that experienced investigators have, in some instances, assumed that welds of similar structure made by this method would also be unsatisfactory.

However, results of test data and service experience have proved conclusively that such assumptions are unfounded, and that, in the as-welded condition, the welds possess an unusual combination of strength and ductility. It has been shown that in spite of the dendritic structure, the weld metal is more amenable to normalizing and recrystallization than the base metal, as can be seen in Fig. 2. Moreover, it has been definitely es-

tablished that the remarkable protection afforded by the layer of welding material against contamination by the atmosphere has much to do with the exceptional physical properties of the finished weld. In the as-welded condition, the fatigue strength, impact resistance, creep resistance and the normal and high-temperature tensile strength of the welds are generally equal to or superior to the base metal. The test results in Table 1 bear out these facts.

Applications of Process

Submerged melt welding has been successfully applied to a wide variety of steels, including low-carbon and medium-carbon steels; and many of the well-known alloy steels with special properties of heat resistance,

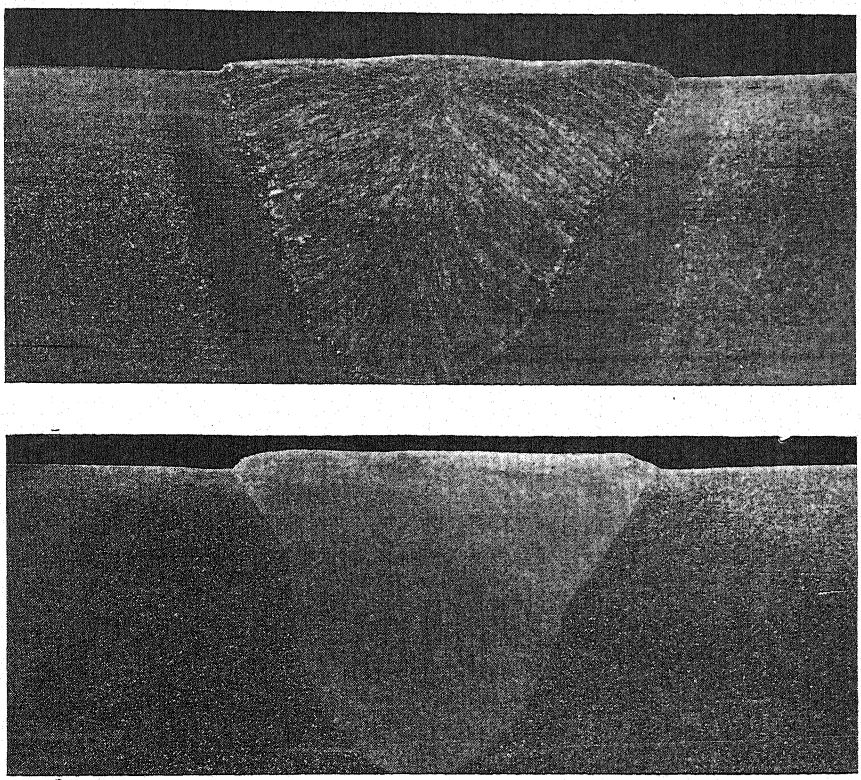


Fig. 2—A Submerged Melt Weld in 2-In. Thick Plate

Although of dendritic structure, the weld metal of submerged melt welds is more amenable to normalizing and recrystallization than the base metal. The upper illustration shows the macrostructure of the 2-in. thick joint as-welded. The lower illustration shows the same weld after having been heated for 2 hr. at 950°C. The columnar structure has been almost completely removed.

Table 1—Section 4—Properties of Various Steels and Alloys in Sheet and Thin Plate Thicknesses

Type of Steel	Condition	Yield Point Psi.	Ultimate Strength Psi.	Elongation 2 In.	Reduction Area	Charpy Impact Ft-Lb.
Armco iron	Plate A.R.	26,000	42,000	22	65	..
Transverse weld specimen (14 gage)	A.W.	31,000	43,700	23	..	..
Stainless steel Non-stabilized 18 gage cold rolled	Plate A.R.	123,000	155,000	15	..	..
Transverse weld specimen	A.W.	83,000	107,000	6	..	..
Cb stabilized 18 gage cold rolled	Plate A.R.	134,000	174,000	7	..	..
Transverse weld specimen	A.W.	81,000	99,500	5	..	..
Ti stabilized 18 gage cold rolled	Plate A.R.	132,000	175,000	5.5	..	..
Transverse weld specimen	A.W.	82,000	101,000	7	..	..
Hastelloy alloy B ($1/4$ in. thick)	Annealed	60,000	130,000	40	40	..
Transverse weld specimen	A.W.	55,000	104,000	16	..	..
	Annealed	57,000	115,000	22	..	..

Table 1—Section 5—Properties of Welds in Non-Ferrous Metals

Type of Steel	Condition	Yield Point Psi.	Ultimate Strength Psi.	Elongation $1\frac{1}{2}$ In.	Reduction Area	Charpy Impact Ft-Lb.
Nickel 0.505 all weld metal	A.W.	23,000	55,200	32.7	43.5	55.6
Reduced transverse weld specimen	A.W.	28,000	55,600	21.0	..	..
Per cent elongation in free bend—45%—failure in center of weld						
Limiting fatigue stress of weld metal (10,000,000 reversals) —29,500 psi.						
Charpy impact test of weld metal: at room temperature —55.6 ft-lb.						
Charpy impact test of weld metal: at −108°F. (− 78°C.) —37.5 ft-lb.						
Charpy impact test of weld metal: at −297°F. (−183°C.) —12.0–58.0 ft-lb.						
Monel 0.505 all weld metal	A.W.	26,600	62,400	45.7	59.4	42
Reduced transverse weld specimen	A.W.	36,900	70,300	45.0	..	..
Per cent elongation in free bend—50% (180° without failure)						
Limiting fatigue stress of weld metal (10,000,000 reversals)—34,000 psi.						
Charpy impact test made at room temperature						
Everdur ($1/2$ in. thick) 0.375 all weld metal	A.W.	16,300	48,000	70	60	31
Per cent elongation in free bend—72% (180° without failure)						

	Plate Material	Weld Metal
Charpy impact test at room temperature	83 ft-lb.	31 ft-lb.
Charpy impact test at − 78°C.	75 ft-lb.	36 ft-lb.
Charpy impact test at −183°C.	74 ft-lb.	35 ft-lb.

Charpy impact tests made with keyhole notch.

corrosion resistance and high strength. Nickel, Monel, Everdur and other non-ferrous metals have also been successfully welded.

There are two features of the process which contribute to its successful application to many different steels and metals. One is the complete protection provided for the weld metal during the operation, preventing oxidation of those alloying elements which are generally easily oxidized. The other important feature is the fact that there is generally about one and a half to two times as much fused base metal as welding rod in the resulting fused zone, as shown in Fig. 3. This means that the weld metal partakes of the properties and chemical composition of the base metal more

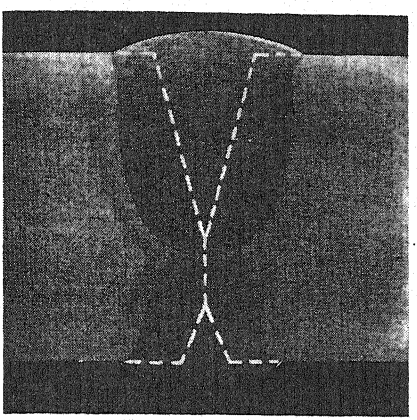


Fig. 3—Weld Metal Has Much of the Properties and Chemical Composition of the Base Metal, Due to the Fact That, in the Fused Zone of the Weld, There Is One and a Half to Two Times As Much Fused Base Metal as Welding Rod. The Dotted White Lines Indicate the Edge Preparation

Table 1—Section 6—Fatigue Properties (Rotating Beam)

Weld No.	Type of Steel
1	Submerged melt weld in rimmed steel 2 in. thick (S-1; A.S.T.M. A-70)
2	Submerged melt weld in silicon-killed steel $2^{5}/_{16}$ in. thick (S-42; A.S.T.M. A-201—39T)

Weld No.	Condition	Yield Point	Ultimate Strength	Elongation 2 In.	Reduction Area	Charpy Impact	Limiting Stress (10,000,000 Reversals)
1	A.W.	43,500	62,700	30.7	57	36.5	32,000–35,000
1	S.R.	35,000	59,200	35.5	66	33.5	32,000–35,000
1	N*	32,700	54,700	39.0	67.5	36.8	32,000–35,000
2	A.W.	47,100	68,200	28.7	51.5	25.8	35,000–38,000
2	S.R.	37,700	63,000	33.7	63.8	31.2	35,000–38,000
2	N*	38,200	60,250	35.8	64	32.5	35,000–38,000
	Plate A.R. silicon-killed steel $2^{5}/_{16}$ in. thick—longitudinal						30,000
	Plate A.R. silicon-killed steel $2^{5}/_{16}$ in. thick—transverse						30,000

* Normalized.
Charpy impact tests made at room temperature using keyhole notch.

nearly than it does in welding processes in which only small quantities of the base metal are fused with the added welding rod. Table 1, Section 2, presents data indicating the excellent physical properties of the welds made in many of the commonly used alloy steels.

The process is now being widely used for fabricating pipe, boilers, pressure vessels, railroad cars and railroad car tanks, ships, rotary kilns, kettles, machinery frames and parts, structural shapes and various other products. It is also used for such types of work as the building-up of worn surfaces and the repair of steel castings.

Equipment and Supplies Required

Welding Heads

In this welding process, the specially designed welding heads most frequently used perform the triple function of progressively depositing the special granulated material along the welding vee, feeding welding rod into the welding zone, and transmitting welding current to the welding rod. The granulated material is usually supplied from a hopper, either mounted directly on the head or connected to the head by tubing. The bare welding rod is fed into the welding head in straight lengths or from a coil of rod mounted on a rod reel. The distance between the end of the welding rod and the base metal is maintained constant by a special automatic control which regulates the rod feed by translating any slight variations in voltage across the welding zone into compensatory variations in the operation of the rod-feed motor.

Table 1—Section 7—High Temperature Tensile Tests*

Weld No.	Quality Plate	Analysis of Weld Metal: Per Cent C	Per Cent Mn	Per Cent Si	Per Cent Mo
R 36	Rimmed steel S-1; A-70	0.14	0.62	0.29	..
S 36	Si-killed steel S-42; A-201—39T	0.17	0.60	0.47	..
M 36	Carbon-molybdenum steel S-44; A-204—39T	0.13	0.80	0.41	0.31
M 40	Carbon-molybdenum steel S-44; A-204—39T	0.13	0.80	0.38	0.48

Weld No.	Testing Temp. °F.	Yield Point Psi. Base Plate	Yield Point Psi. All Weld Metal	Ultimate Strength Psi. Base Plate	Ultimate Strength Psi. All Weld Metal	Per Cent Elongation 2 In. Base Plate	Per Cent Elongation 2 In. All Weld Metal	Per Cent Reduction Area Base Plate	Per Cent Reduction Area All Weld Metal
R 36	800	28,000	37,000	65,250	75,000	28.5	24.0	50.3	39.4
R 36	900	24,000	37,500	52,000	62,250	29.0	25.0	62.8	57.5
S 36	900	25,500	32,500	57,250	59,000	28.0	26.0	62.8	57.0
S 36	1000	27,500	29,000	43,250	46,000	27.0	26.5	66.1	58.6
M 36	900	46,500	46,000	73,500	77,000	20.0	23.0	44.3	49.5
M 36	1000	38,000	41,500	62,500	62,000	17.0	19.0	46.6	56.8
M 40	900	45,000	54,500	75,500	87,000	21.0	19.0	46.3	41.6
M 40	1000	44,000	55,000	64,500	77,250	18.0	16.0	48.9	48.1

* Standard short-time high-temperature tension test.
Remarks: All failures cup and cone.

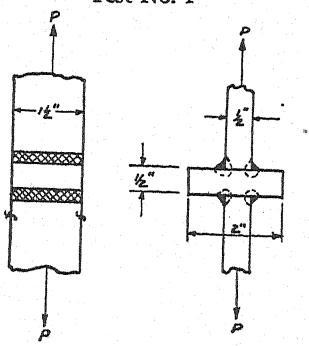
Three sizes of welding heads are made available by the sponsors of the process.

A large head known as the Type M, weighing about 435 lb., is available

Table 1—Section 8—Strength of Non-Positioned Fillet Welds

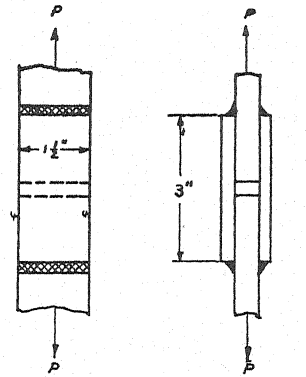
TRANSVERSE SHEAR TESTS

Test No. 1



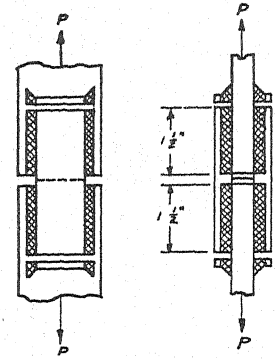
TEST	SPECIMEN	FILLET SIZE*	BREAKING LOAD "P"	FILLET LOAD LB./LINEAR IN.	FRACTURE
No. 1	A	3/16 in.	39,450	13,200†	Plate
	B	1/4 in.	47,350	15,800†	Plate
	C	5/16 in.	47,600	15,900†	Plate

Test No. 2



TEST	SPECIMEN	FILLET SIZE*	BREAKING LOAD "P"	FILLET LOAD LB./LINEAR IN.	FRACTURE
No. 2	1	5/16 in.	69,000	23,000	In weld
	2	5/16 in.	71,000	23,700	In weld
	3	3/8 in.	72,000	24,000	In weld
	4	3/8 in.	73,000	24,300	In weld

LONGITUDINAL SHEAR TESTS



SPECIMEN	FILLET SIZE*	BREAKING LOAD "P"	FILLET LOAD LB./LINEAR IN.	FRACTURE
1	5/16 in.	97,000	16,200	In weld
2	5/16 in.	94,000	15,700	In weld
3	3/8 in.	104,000	17,300	In weld
4	3/8 in.	100,000	16,700	In weld

* Fillet sizes given are from measurement of vertical leg.

† Full strength of fillet welds with submerged melt process not developed as fracture occurred in plate.

NOTE: Due to greater depth of penetration, much smaller fillet welds may be employed in the submerged melt welding process than with other processes without sacrificing strength. The American Bureau of Shipping has permitted some shipbuilders to use 1/16 in. to 1/8 in. smaller submerged melt fillet welds than specified manual metallic arc-weld size.

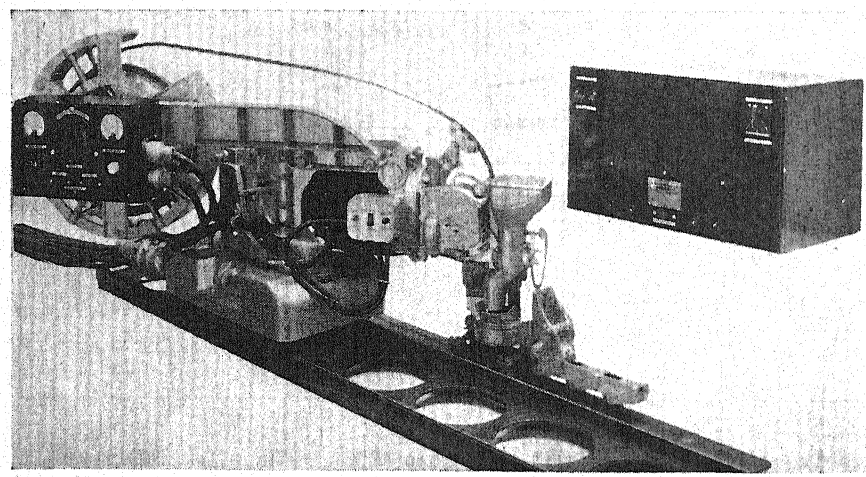


Fig. 4—The Type U Head Can Be Mounted on a Portable Carriage. The Main Control Unit, Shown in the Upper Right, Is Located at a Stationary Point. The Operating Panel Has Been Removed and Mounted on the Machine for Control by the Operator at the Welding Head

for heavy production welding. It will feed coiled rod or straight rod in any size up to $^1/_2$-in. diameter, will handle currents up to approximately 4000 amperes and is capable of making single-vee one-pass butt welds in steel $2^1/_2$ in. thick.

An intermediate-size head known as the Type U, weighing about 125 lb., will feed coiled or straight rod in any size up to $^5/_{16}$-in. diameter, will handle currents up to approximately 2000 amperes and will make deposits heavy enough to weld steel up to $1^1/_4$ in. thick in one pass. See Fig. 4, which shows this head mounted on its own portable carriage.

A small-size head known as the Type S, weighing about 15 lb., will feed only straight lengths of welding rod up to $^1/_4$-in. diameter which is generally used either in the 16-ft. lengths as usually supplied or in shorter lengths cut on the job. It will handle currents up to approximately 1000 amperes, and will weld steel $^1/_2$ in. thick in one pass.

The examples of maximum thickness which each head is capable of welding in one pass do not indicate the thickest material for which the equipment is useful. With double-vee joints, approximately twice the thickness mentioned can be welded by making a single-pass from each side. Multi-pass welding can be used for greater thicknesses.

Electrical Equipment

This welding process uses either alternating or direct current at from 20 to 55 volts across the welding zone. As previously mentioned, currents are much higher than those used with arc-welding processes, and range, for the largest available standard equipment, up to 4000 amp.

Alternating current is most frequently used, principally because the installation costs and maintenance costs of current-producing equipment are usually less. Heavy-duty welding transformers with built-in, motor-controlled reactors are standard products of several manufacturers of electrical equipment. Transformers in 1000-amp.-capacity units (1000 amp. for one hour of operation, 750 amp. for continuous operation) are generally employed, although both larger and smaller units are being used. Currents higher than those obtainable from one transformer are obtained by connecting two or more units in parallel. Direct-current welding generators of similar characteristics are sometimes used with their output circuits connected in parallel.

Most installations are arranged so that all manually adjustable controls are located near the welding head in a position convenient to the operator of the equipment. These include controls for welding voltages and amperage, for regulating the rod feed, and for moving the welding head in relation to the workpiece.

Welding Composition

The granulated welding material is available in various grades, of slightly different compositions. Each grade is available in various ranges of particle sizes. The choice of grade and size is dependent on the composition of metal being welded, the thickness of metal, the design of the weld, the quantity of current used, and the speed of welding. These factors have been determined and tabulated for various types of work.

The size of particles used considerably affects the nature of the weld. It is generally more desirable to use the coarser sizes on light-gage material and with lower currents, and to use the finer sizes for thicker base metal and higher currents.

Welding Rod

This process uses generally a copper-drawn bare steel welding rod having no coating or covering. Several types and sizes of bare welding rod have been specially developed for use with the process and are available for welding wide varieties and thicknesses of steels.

Accessory Equipment

Welding installations are arranged in many different forms, depending

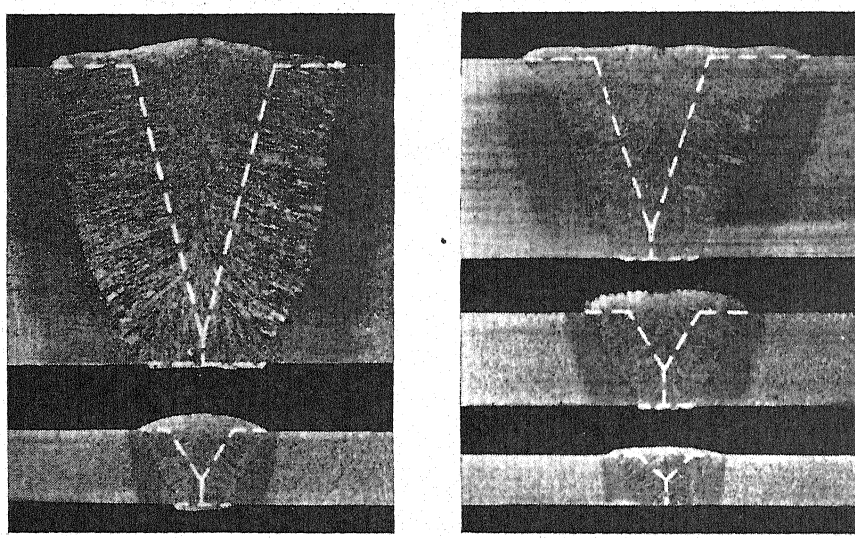


Fig. 5—These Etched Cross-Sections Show One-Pass Butt Welds Made in $^1/_4$-In., $^3/_8$-In., $^1/_2$-In., 1-In. and $1^1/_2$-In. Steel Plate with Suitable Backing to Insure Complete Penetration

on the type of welding head used, the nature of the work to be welded and the space and equipment facilities available. Installations do not necessarily require a large capital outlay for new equipment. Frequently apparatus and equipment which are already available can be adapted to make a satisfactory welding setup.

Any of the welding heads can be mounted either on a stationary support under which the work is moved, or on a support which travels over the work to be welded; or in some instances, a special rod holder can be moved by hand. Commonly used intermediate and small-sized heads can be mounted on a portable, electric motor-driven carriage which rides directly on the workpiece or on portable sections of track.

The portable equipment is desirable for welding long seams in metal of thickness not exceeding $1^1/_4$ in., particularly where the welding equipment is used on fabrication of structures that cannot conveniently be moved from place to place. For shops using this welding process in the repetitive fabrication of pressure vessels, tanks, pipe and similar work of relatively large size, the welding head is frequently mounted on a light wall crane or gantry crane. In welding machinery parts and relatively small structural units held in positioners or jigs, the welding head is usually so mounted that it can travel over two or more jigs arranged in such a way that positioning of the work, welding and removal of welded assemblies can be carried on with most efficient use of equipment.

For pressure-vessel, boiler and tank construction, one of the smaller heads can be mounted on the end of a cantilever for insertion into the shell to make both longitudinal and circumferential welds from the inside, as the end and various courses are assembled.

Type of Welds

This welding process is used for making butt welds, fillet welds and plug welds. Regardless of the kind of weld being made, quality of the finished product is influenced considerably by the cleanliness of the edges to be welded, and the care taken in effecting good alignment and "fit up" of the parts to be welded.

Butt Welds

Butt welds are commonly made in one or two passes in any thickness of steel from 16 gage to 3 in., and at speeds ranging from 3 to 80 in. per min. Steel up to $2^1/_2$ in. in thickness can be welded in a single pass. Etched cross-sections of one-pass welds in $^1/_4$-in., $^3/_8$-in., $^1/_2$-in., 1-in. and $1^1/_2$-in. steel plate are shown in Fig. 5. Heavier materials, such as slabs up to 5 in. in thickness, have also been welded by this process, by multiple passes from one side or by making two welds, one on each side of the joint. Fig. 6 shows a cross-section view of a double-welded butt weld in $3^1/_4$-in. steel plate.

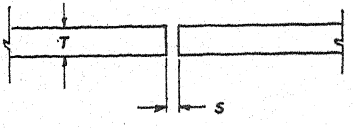
Joint Preparation.—In practice, preparation of plates to be welded involves operations comparable to edge preparation required for arc welding or oxyacetylene welding. However, because of greater penetration obtainable with submerged melt welding, material of considerable thickness can be welded with no bevel preparation. For single-vee welds the edges are only partially beveled so that a square portion, the root face or "nose," remains and subsequently is completely fused into the weld. For welds made from two sides, preparation may consist of beveling each side of the edge so as to leave a square portion or root face in the center. Materials of $^1/_8$-in. thickness or less are frequently double welded with one pass from each side without any beveling. Welds made from two sides can be made to overlap without cutting away the abutting unbeveled portions or cutting into the bottom of the first weld.

The space in the form of a vee, or the opening between abutting square edges of a backed open-square butt joint can be much narrower with this process than with other welding methods because penetration and width

of the finished weld are greater. The bevels can be made by oxyacetylene cutting or by planing. Light scale on the edges of an oxyacetylene cut need not be removed, but heavy mill scale and rust, oil, paint, grease, and other substances from which gas might evolve should be removed from the surfaces within or near the area of fusion when making high-quality welds. Visible moisture in the welding zone makes it difficult to produce sound welds, and should be removed. When oxyacetylene cutting is used for preparing edges for butt welds, the heat will remove most objectionable surface materials and may crack off sufficient mill scale along the edge to make grinding, sandblasting, or scale removal by other methods unnecessary.

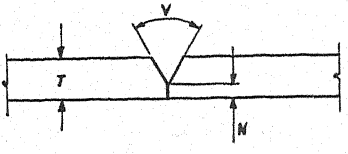
Weld Backing.—For making butt welds in one pass where complete penetration is desired, the highly fluid weld metal must be supported. This is generally done by means of a closely fitted copper backing bar, which may be straight or circular depending on the type of butt weld being made.

Table 2—Typical Production Welding Conditions for One-Pass Butt Weld in Low-Carbon Steel



Copper or *Melt Backing

Thickness T	Spacing S	Welding Rod Diam.	Welding Rod Lb./Ft.	AC Welding Current Amp.	AC Welding Current Volts	Speed In./Min.
10 ga.	0–1/16	5/32	0.07–0.08	575–650	24–27	45–50
3/16†	0–1/16	3/16	0.11–0.13	575–650	25–27	32–36
1/4†	0–3/32	3/16	0.14–0.23	750–850	27–29	30–34
5/16†	0–3/32	1/4	0.25–0.30	800–900	26–30	26–29



Copper or Melt Backing

T	V	N	Welding Rod Diam.	Welding Rod Lb./Ft.	AC Welding Current Amp.	AC Welding Current Volts	Speed In./Min.
3/16†	60°	1/8	3/16	0.11–0.13	500– 575	28–31	29–33
1/4†	60	1/8	3/16	0.14–0.23	725– 825	29–32	28–31
3/8	60	1/8	1/4	0.28–0.35	900–1000	32–36	24–27
1/2	60	3/16	1/4	0.38–0.45	1075–1175	34–37	20–23
3/4	45	3/16	1/4	0.60–0.75	1200–1300	36–39	13–14
1	35	1/8	5/16	0.90–1.10	1500–1600	39–41	10–12
1 1/4	30	1/8	5/16	1.25–1.60	1600–1700	39–41	8– 9
1 1/2	30	1/8	3/8	1.85–2.00	1900–2000	40–43	7– 8

* The term "melt" is generally used in shop practice to identify the granulated material.

† Vee preparation facilitates guidance and improves weld appearance.

Note: The weight of melt consumed (amount fused) is 85% to 100% of the weight of rod deposited.

The necessary pressure to effect close contact between bar and seam is usually provided by some type of compressed-air jack or inflated hose which sometimes is built into a jig.

A steel strip can also be used as backing and becomes a part of the joint. Another method is to back up the weld with granulated welding composition. Sometimes a trough filled with the material is held against the underside of the seam. A flexible hose is placed in the bottom of the trough and, when inflated, pushes the composition up with a uniform pressure against the bottom of the weld. Another variation is to fill a cotton tube with the composition material and hold it in position on the underside of the seam. Table 2 gives typical welding conditions for making single-pass butt welds using a copper or welding-composition backing.

In some instances it may be desirable to apply by manual metallic arc welding one or two layers of weld metal on the underside of the seam to serve as a backing for a deeply penetrated weld made along the other side. Table 3 gives typical welding conditions for making double-vee butt welds with manual arc-welded backing. A cross-section of this type of weld is shown in Fig. 7.

Figure 8 illustrates two types of corner joints made by this process of welding. One was completely made with a one-pass butt weld backed by a steel strip, while the other was made in two passes, the main butt weld being backed by a fillet weld.

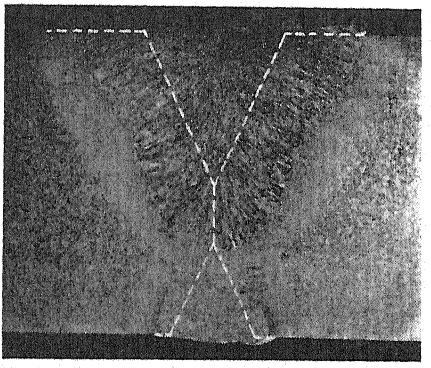


Fig. 6—This Is an Etched Cross-Section of a Double-Welded Butt Weld in $3^1/_4$-In. Steel Plate

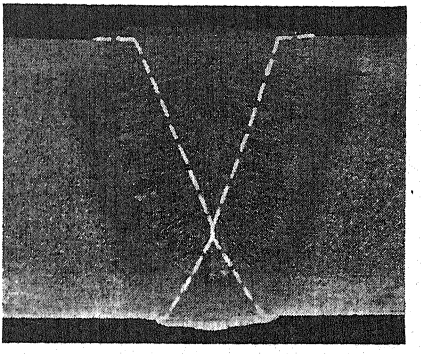
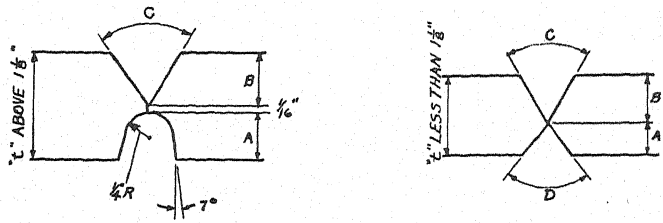


Fig. 7—This Cross-Section of a Double-Vee Butt Weld Shows a Submerged Melt Weld with Manual Arc-Welded Backing

In making butt welds in plate of a thickness of $^1/_2$ in. or greater, particularly in pressure-vessel construction, it is accepted practice to double weld, i.e., to make two welds, one on each side of the plate. Figure 9 shows a cross-section view of a two-pass butt weld with double-vee edge preparation. This technique usually eliminates the necessity for auxiliary backing. The square unbeveled root faces or "noses" in the center must be butted tightly together so that the first weld, made with limited penetration, will be supported. The first weld then serves as backing for the more

Table 3—Double-Vee Butt Welds with Manual Backing Pass; Typical Production Welding Conditions for High Quality Welds in Steels Following A.S.M.E. Specs. S-1, S-55, S-44



Thickness t	Min. I.D. of Vessel	Finishing Pass B	C	Amp.	Volts	Speed	Rod Diam.	Backing Pass (Manual) A	D
1/2	14	1/4	60	900	38	16	1/4	1/4	90
3/4	18	3/8	60	1050	38	14	1/4	3/8	90
1	22	5/8	60	1200	38	11	1/4	3/8	90
1 1/4	32	11/16	45	1500	40	10	5/16	1/2	U
1 1/2	42	11/16	45	1600	40	9	5/16	3/4	U
	60	15/16	40	1700	40	9	5/16	1/2	U
1 3/4	44	13/16	45	1600	40	9	5/16	7/8	U
	72	1 1/16	40	1800	40	8	5/16	5/8	U
2	44	13/16	45	1600	40	9	5/16	1 1/8	U
	96	1 5/16	35	2200	40	7	3/8	5/8	U*
2 1/4	44	13/16	45	1600	40	9	5/16	1 3/8	U
	96	1 7/16	30	2400	40	6	3/8	3/4	U*

* If current is limited to 2000 amp., use B = 1 3/16 in., C = 40° at 40 volts, 8 in. per min., and increase accordingly the depth A.

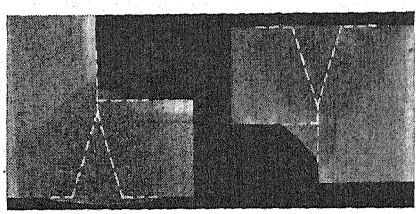


Fig. 8—On These Corner Joints Made in 1-In. Steel Plate, the One on the Left Was Made in One Pass Backed by a Steel Strip, While the One on the Right Was Made in Two Passes, the Main Butt Weld Being Backed by a Fillet Weld

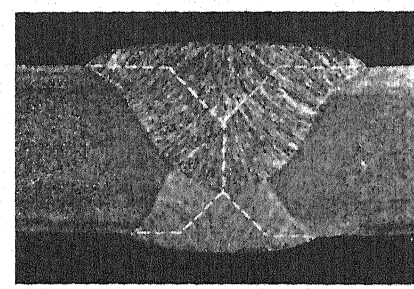


Fig. 9—In Making Butt Welds in Plate of 1/2-In. or Greater Thickness, Two Welds May Be Made, One on Each Side of the Plate, as Shown Here

deeply penetrated second weld, made from the opposite side. With this joint design it is important that the unbeveled root face be of sufficient thickness to support the first weld, and yet not so thick as to prevent complete penetration and fusion of the second weld into the first weld. Table 4 presents typical production welding conditions for high-quality welds made by double-bevel welding technique.

Fillet Welds

It has been established that because of the greater depth of penetration

of welds made by this process fillet welds may be made much smaller than with other processes, without sacrificing strength. Consequently these smaller fillet welds have generally been accepted for shipbuilding and for the fabrication of heavy structural shapes such as bases, frames and girders for railroad and industrial equipment.

Fillets up to 3/8 in. in leg dimension can be made without positioning the work. The more usual practice for fillet welds, however, is to tilt the structure at an angle of 20 to 45° from the horizontal so that the weld surface is more nearly horizontal. For welding fillets of 1/2-in. leg size or slightly greater, some success has been obtained without positioning by making one deposit on the horizontal surface close to the intersection and another deposit in the slight vee-space which results between this weld and the vertical surface. Figure 10 shows cross-section views of T-butt joints in 1/2- and 3/4-in. steel plate made with two one-pass fillet welds.

Lap joints can also be made by means of fillet welds, as shown in Fig. 11. Table 5 presents conditions for fillet welds in the commonly encountered ranges of thickness.

Joint Preparation.—For fillet welding, no bevel is required to obtain complete penetration and center overlap of fillet welds made from both

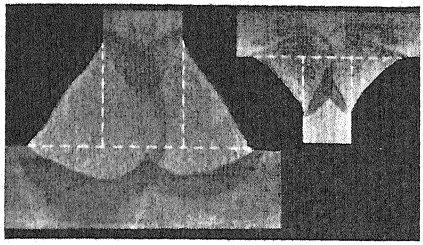
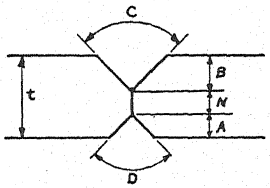


Fig. 10—This Cross-Section View Shows T-Butt Joints in 1/2-In. and 3/4-In. Steel Plate Made with Overlapping One-Pass Fillet Welds

Table 4—Double-Vee Butt Welds; Typical Production Welding Conditions for High Quality Welds in Steel Conforming to A.S.M.E. Specs. S-1, S-55, S-44



Thickness t	Min. I.D. of Vessel	Finishing Weld							Backing Weld						
		B	C	Amp.	Volts	Speed	Rod Diam.	N	A	D	Amp.	Volts	Speed	Rod Diam.
1/2	14	1/8	90°	900	38	16	1/4	1/4	1/8	90	700	35	18	1/4
3/4	21	1/4	90	1150	38	13	1/4	5/16	3/16	60*	900	35	18	1/4
1	24	3/8	90	1300	38	12	1/4	5/16	5/16	60*	1000	35	17	1/4
1 1/4	30	1/2	70	1400	38	11	5/16	3/8	3/8	60	1100	35	15	1/4
1 1/2	36	5/8	60	1550	38	10	5/16	7/16	7/16	50	1200	35	12	1/4
1 3/4	44	5/8	60	1650	38	9	5/16	1/2	5/8	45	1450	35	10	5/16
2†	44	3/4	50	1650	37	9	5/16	1/2	3/4	45	1600	38	10	5/16
2 1/4†	44	1	45	1700	37	8	5/16	1/2	3/4	45	1600	38	9	5/16

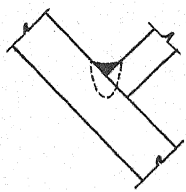
* Tabulated conditions give 1/8 in. reinforcing. If less reinforcing (1/16 in.) is desirable, use D = 90°.
† For circumferential seams install backing weld on outside for diameters from 44 to 72 in.

sides in T-butt joints in plate up to approximately 3/4 in. thick. It is recommended that the edges of plate of greater thicknesses be beveled to insure complete overlap of welds.

Plug Welds

Submerged melt welding has been used with unusual effectiveness in the making of high-quality plug welds. The etched cross-section of such a plug weld, shown in Fig. 12, indicates the penetration and uniform fusion between the plates.

Table 5—Positioned Fillet Welds
Positioned at 45° *



Normal Fillet Size	Amp.	Volts	Speed In./Min.	Welding Rod Diam.	Welding Rod Lb./Ft.
3/16 in.	500	27	32	1/8 in.	0.07
1/4 in.	650	27	28	3/16 in.	0.11
5/16 in.	650	28	22	3/16 in.	0.17
3/8 in.	750	29	18	3/16 in.	0.25
1/2 in.	850	31	16	1/4 in.	0.43
5/8 in.	950	31	13	1/4 in.	0.66
3/4 in.	1080	31	11	1/4 in.	0.95

* Fillets up to 3/8-in. leg may be made without positioning.

Note: These conditions if used in applying a fillet to each side of the web plate will yield 100% penetrated tee joints with the work positioned at 45° where the thickness of the web plate is equal to or less than the size of the fillet leg.

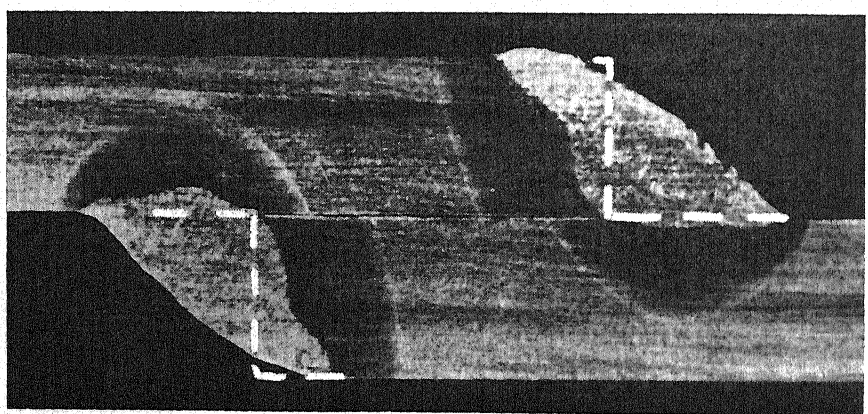


Fig. 11—This Lap Joint Was Made with Two Fillet Welds

The same equipment used for seam welding can be used for plug welding by this process, except that when portable equipment is used, no track is necessary since for each plug weld the machine remains stationary. When starting a plug weld, the machine is simply rolled into position so that the welding rod enters the center of the hole to be welded. Steel wool or other starting fuse material is then placed in the hole, the rod lowered so as to touch the fuse, and sufficient welding composition allowed to flow down so as to surround completely the end of the welding rod. The current need be turned on only for a few seconds, to complete the weld. Table 6 presents typical welding conditions for making plug welds, and Fig. 13 shows a plug weld in the making.

The plug-welding technique has also been successfully used in the welding of stay bolts. Figure 14 shows a typical cross-section of such a stay-bolt weld.

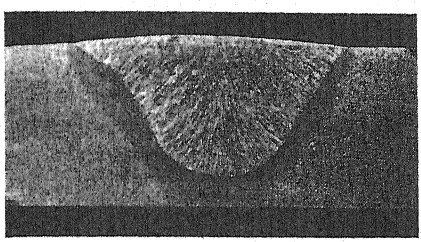
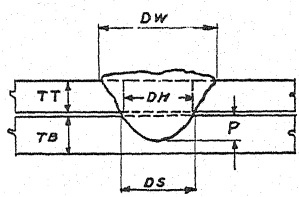


Fig. 12—This Etched Cross-Section of a Plug Weld Illustrates the Penetration and Fusion Between the Plates

Table 6—Welding Conditions for Plug Welds



TT	Min. TB	DH	Rod Size	Amp.	Volts	Seconds to Weld	Length of Rod—in.	Rod Lb.*	Melt Lb.	DW In.	P In.	DS In.	Shear Area In.
1/4	3/16	5/16	3/16	900	25	..	0.79	0.0062	0.02	13/16	1/8	3/8	0.110
	3/16	7/16	1/4	800	25	..	0.88	0.0122	0.02	7/8	5/32	7/16	0.150
5/16	5/16	7/16	1/4	950	25	..	1.09	0.0152	0.03	1	7/32	1/2	0.196
	5/16	11/16	1/4	900	25	3	2.71	0.0377	0.03	1 1/8	3/16	11/16	0.371
3/8	5/16	9/16	1/4	1000	25	3	2.18	0.0303	0.03	1 1/8	3/16	9/16	0.248
	3/8	13/16	1/4	950	25	6.5	4.57	0.0634	0.04	1 1/4	9/32	13/16	0.518
7/16	3/8	11/16	1/4	1050	27	5	3.81	0.053	0.04	1 3/8	1/4	11/16	0.371
	7/16	13/16	1/4	1000	27	7	5.32	0.074	0 05	1 1/2	5/16	13/16	0 518
1/2	7/16	11/16	1/4	1100	28	6.5	4.32	0.060	0.05	1 5/8	9/32	3/4	0.442
	3/8	13/16	1/4	1050	28	10	6.05	0.084	0.07	1 3/4	5/16	7/8	0 601
5/8	7/16	13/16	1/4	1200	30	8	7.50	0.104	0.10	1 3/4	5/16	13/16	0.518
	1/2	15/16	1/4	1100	33	11	10.02	0.140	0.30	2 1/8	3/8	1 1/16	0.887
3/4	1/2	13/16	1/4	1300	30	11	9.2	0.126	0.14	1 7/8	3/8	7/8	0.601
	1/2	1 1/16	1/4	1200	35	24	15.6	0.217	0.41	2 5/8	3/8	1 1/4	1.277

* Calculated amount plus 15% for reinforcement.

Preheat and Post-Weld Requirements

The use of this welding process simplifies preheat requirements in fabrication of some types of materials, particularly the high-strength structural steels.

For example, one company has reported that, in constructing pressure vessels of 1 in. thick, 5% chromium, heat-resistant steel by ordinary welding methods, they had found it necessary, because of the "air-hardening" characteristics of the metal, to keep the vessel hot during welding.

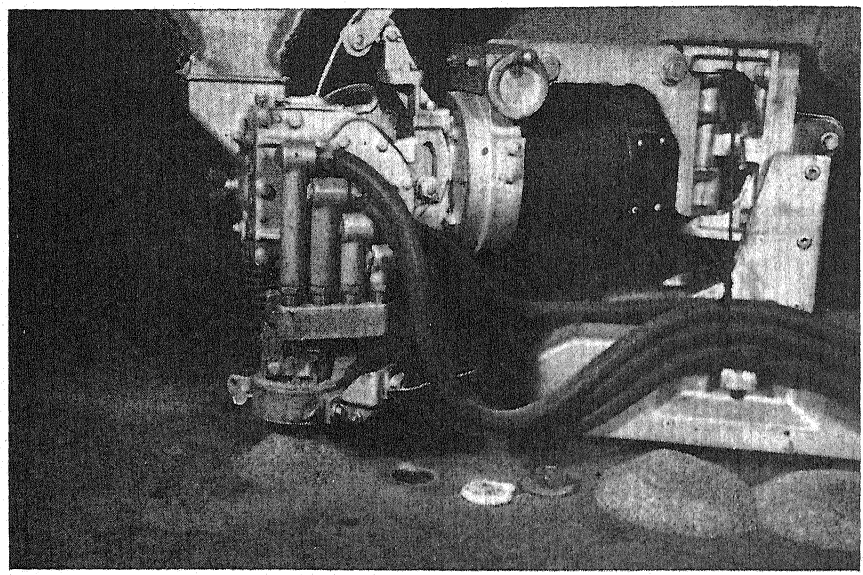


Fig. 13—Here a Plug Weld Is Being Made. Just to the Right of the Weld Being Made Is a Completed Weld, with the Fused and Unfused Material Removed. The Two Piles of Material on the Right Are Covering Completed Welds

This was a costly procedure, particularly since the vessel had to be reheated several times before the weld could be completed, and the welding operator needed special protection against the heat. By welding the vessel with this new welding process, it was possible to complete the weld in one pass, with but one heating to about 200° F. This welding method materially improved the quality of the vessel and reduced the production time. Slag inclusions, porosity, cracking and lack of fusion, which had frequently resulted from the extremely uncomfortable working conditions under which the operators were formerly required to make the multiple-bead, manual welds, were avoided. The time-consuming and costly procedures of chipping, reheating, re-stress relieving and re-examining by X-ray were therefore avoided.

Another common post-weld problem which is either avoided or minimized in submerged melt welding is the need for correcting distortion. In this process intense heat is rapidly applied in a confined space. The

entire cross-section of the weld is molten at one time, and the speed of welding allows but little of the welding heat to enter into the zones adjacent to the weld. This combination of complete fusion and rapid weld progress minimizes distortion and reduces the total contractional stress.

One striking example of this freedom from distortion is provided in the construction of the modern Pullman car, in which the process is used quite extensively. The sides of each car are fabricated from sections of 14-gage steel sheet, one joint of which is a one-pass weld extending the entire length of the car. The finished side is smooth and free from distortion; no flattening is required.

Heavy materials are also being welded with minimum distortion. Crane girders, dipper sticks and heavy girders and beams for bridges and ships are being fabricated by this welding process without need for expensive post-weld straightening.

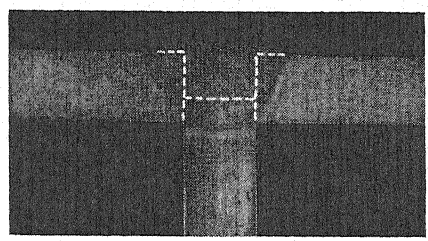


Fig. 14—This Is a Typical Cross-Section of a Stay-Bolt Weld

Operator Requirements

To operate submerged melt welding equipment properly and competently, the operator does not need the highly developed skill of manual welding. The operator must be able to follow directions giving him the proper voltage, amperage and speed requirements for a particular thickness of metal, type of joint and detail of edge preparation. He must be able to follow directions on the selection of the proper granulated material and welding rod for any one job. Finally he must be familiar with the proper procedures of aligning and positioning the work and the welding machine, must be able to recognize deviations from the desired joint preparation, and make compensating adjustments of current, voltage and speed. Once the welding machine is set up to operate, however, the operator's duties consist largely of pushing control buttons and observing conditions. He wears no shield, goggles, helmet or protective breathing apparatus since no smoke, flash or sparks are given off during welding. The operator is not subject to the usual fatigue associated with manual welding, and no continuous exercise of care and skill is necessary to assure the high quality of each portion of weld.

Reducing the importance of "the human element" in making welds is a great advantage in that it simplifies the task of maintaining uniform quality

of the welds. When conditions are properly established at the start to produce a satisfactory weld, the good results will continue provided the quality and edge preparation of the base metal remain the same, and provided the controls of the welding machine are set for the desired values.

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RESISTANCE WELDING SECTION

This section of the Handbook (Chapters 8–12, inclusive) was prepared under the sponsorship of the Resistance Welder Manufacturers Association, which organization has cooperated with both the AMERICAN WELDING SOCIETY *in general and the A. W. S. Handbook Committee in particular. The R. W. M. A. was instrumental in selecting committee personnels for preparation of the various chapters and maintaining the high standards of authorship that have prevailed. The Handbook Committee gratefully acknowledges the assistance received from that Association, from the member companies of the Association, and from the individuals connected with those member companies, in connection with the preparation of the following Chapters.*

NOTE: *Coordination of the Resistance Welding Chapters was under the supervision of the following committee:*

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For a complete explanation of the terms used in Resistance Welding Chapters, refer to the Definitions in Chapter 43.

CHAPTER 8

FUNDAMENTALS OF RESISTANCE WELDING*

General Theory, Economics of Resistance Welding, Electrical Characteristics of Resistance Welders, Power Supply and Installation, and Mechanical Characteristics of Resistance Welders.

A. GENERAL THEORY

RESISTANCE welding embraces that branch of the welding art in which the welding heat in the parts to be welded is generated by the resistance offered by these parts to the passage of an electric current. It differs from other forms of welding in that no extraneous materials, such as fluxes, filler rods, etc., are used, therefore the metallography of the weld is not complicated by the addition of these materials. The total heat, however, is not always generated by resistance alone, as there are two or three notable exceptions to this, such as flash-butt welding and percussive welding. In the latter process (see Chapter 9) the heat is entirely generated by an intense spark gap, while in the former, the major portion of the heat is generated by the flashing arc and the combustion of the metal in the arc (see Chapter 9—Flash and Butt Welding).

It may be stated at the outset that resistance welding may be resolved into two major groups or classes as follows:

Spot Welding:	Butt Welding:
Spot	Butt-flash
Projection	Push-butt
Seam	Percussive
Cross wire	Contact
Contact	

It will be noted that in this grouping, *contact welding* may be classified either as *spot* or *butt welding*. This consists primarily of welding the end of a bar, rod or pipe to a sheet, plate or other bar or pipe, one or both of the welding surfaces having been especially prepared by machining or other method, to present a line, circular or annular contact surface, the duration

* Prepared by a committee consisting of E. J. Del Vecchio, The Taylor-Winfield Corp., *Chairman*, G. S. Mikhalapov, The Taylor-Winfield Corp.; S. M. Spice, Buick Motor Company; B. L. Wise, Federal Machine & Welder Co.; H. C. Cogan, National Electric Welding Machines Co.; L. W. Clark, The Detroit Edison Co.

of the weld being controlled by a timing device, and not by methods ordinarily used in butt welding.

As will be shown in the following chapter, practically all metals may theoretically be resistance welded by any of the methods, although some of them are considered commercially impractical (see Chapter 9).

The products that may be resistance welded range from the smallest wires to very heavy sections. By any method, the resulting weld is a forge weld—that is, the actual weld or bonding of metal is accomplished by means of mechanical pressure applied by the welding machine, which pressure refines the grain structure, thus producing a weld with physical properties in most cases equal to the parent metal, and sometimes even superior.

Generation of Heat

It should be noted that with any process of resistance welding the heat is generated within the metal itself, and not by heat absorbed from an outside source. Consequently, the speed of welding is determined by the rate at which heat can be generated. Due consideration must be taken, however, of heat losses such as radiation and conduction into surrounding metal and into the electrodes.

The simple formula for expressing the heat required is:

$$H = I^2RTK$$

in which I = the current in amperes
R = the resistance of work in ohms
K = a factor representing total radiation and conduction losses
T = the time of current flow

The above expression applies to spot, projection, seam, etc., processes, but is not applicable to flash welding because, as above noted, this process is complicated by the addition of heat from the flashing arc as well as the combustion of iron in the arc.

Considering the above formula in spot welding, it is at once apparent that (neglecting radiation and conduction losses) the heat is proportional to the square of the current. If the current is doubled, the heat generated will be quadrupled.

The total heat is also proportional to the total time of current flow. Were it not for radiation and conduction losses, two pieces of metal could be brought to welding temperature with any finite current value. Since radiation and conduction losses are inevitable, it is obvious that the minimum current with which a given weld can be made is that current which can maintain these losses at welding temperature, and longer application of the welding current will not further increase the temperature of the metal at the weld.

It can be shown experimentally, and is indicated by the above formula that to produce a given weld, the welding current is approximately inversely proportional to the square root of the time. That is, if the current is doubled, the time can be reduced 75%. However, as the time gets extremely short, current values become abnormally high, to the extent that heat is not generated principally along the inside or faying surfaces, but throughout the thicknesses of metals resulting in very severe surface mark-

ing and rapid electrode deterioration. The optimum time and current ratio depends upon the application.

The other element of the formula is resistance of the metals, particularly the contact surfaces being welded. The heat generated by the passage of current is directly proportional to the resistance.

In very rough terms, we could say that the amount of heat required to make a given spot weld in two specified thicknesses of metal is approximately the same, regardless of the composition of the metal. Then from the formula it can be seen that the higher the electrical resistance of the metal being welded the less current is required for the weld. Copper and silver having the least resistance are very difficult to weld, not because of the difficulty of providing the necessary current but because no electrodes can satisfactorily carry it. Aluminum, with two-thirds the conductivity of copper, can be readily welded but the current required is high. Steel is relatively easy; but stainless steel, Monel, silicon bronzes and other metals having higher resistance than steel require still less current.

Dissipation of Heat

A study of the properties of the various metals reveals the fact that electrical and heat conductivities closely parallel one another. The metals having high heat conductivity also have high electrical conductivity. In the preceding paragraphs it was shown that the higher the electrical conductivity the more current is required for a given weld. To this, we can also add that the higher the heat conductivity the greater will be the radiation and conduction losses, again adding to the required current to overcome these losses.

Conduction losses are two-fold: (1) conduction into the electrodes; (2) conduction into the surrounding metal. Conduction losses are directly proportional to temperature differentials. The higher the temperature, the greater these losses. The ideal condition for a spot weld is to prevent as much as possible the conduction of heat into the surrounding metal—first, to reduce discoloration; second, to prevent warpage in the parts being welded. Therefore, generally speaking, the best condition for spot welding is where the time is kept as short as possible, thus reducing the extent of heat conduction into the surrounding metal to a minimum.

B. ECONOMICS OF RESISTANCE WELDING

Labor Cost and Selection of Equipment

The labor cost is often the determining factor in the selection of any welding operation. The cost of labor chargeable against any operation is divided into two elements: (1) hourly rate of wages; (2) production per hour. From the combination of these two the labor unit cost is determined.

Resistance welding generally requires less skill on the part of the operator than other methods of welding; consequently, the hourly rate is less. In

small shops, it is necessary to combine the duties of the set-up man and operator, in which case the wage cost will probably be on a par with a gas or arc-welding operator. In large plants, resistance welding machines are generally operated on the same basis as punch presses and production machine tools, where the operator merely operates or feeds the machine and little or no skill is required and the set-ups are performed by foremen or set-up men.

The selection of resistance welder operators is not always as simple as may be inferred from the foregoing, and the various forms of welding require varying degrees of skill or ability.

Spot Welding.—The skill required of a spot-weld man depends both on the nature of the operation and the type of equipment used. Job shop and low volume operations usually call for foot or hand operated equipment, consequently satisfactory results depend to a large measure on the skill and experience of the operator. Also speed of operation, which contributes to the unit cost, is controlled to a large extent by dexterity on the operator's part.

High production jobs can best be performed on power operated machines with all operating variables automatically controlled, in which case, the operator's duties consist only in correctly positioning the work and pushing a button or foot pedal.

Projection Welding.—Since this type of work almost invariably consists of joining two or more stampings, it is axiomatic that the operation be completely automatic. Projection welders are usually provided with locators, fixtures, etc., which make the operation of this machine essentially the same as a punch press.

Where several pieces are to be assembled together, the time required for loading the machine may justify the use of jigs which may be externally loaded and unloaded by helpers. This is a problem, however, that must be determined for each individual case.

Dial feed mechanisms can often be economically applied to press type spot or projection welders, greatly increasing their production. Not only is production greatly increased, but these mechanisms often permit the employment of female labor.

Multipoint Welders.—Medium and large size assemblies are often welded in large production machines in which the number and location of spots is beyond the range of the projection method. Here the labor element is very largely the determining factor in the selection of such a machine.

Portable Spot Welders.—As the bulk of spot-welded assemblies increases, the point is reached where it is more economical to move the welder to the work than to feed the work into a stationary machine. This is especially true where the work is of such nature that one machine set-up cannot be used for all welds. Another factor influencing the use of portable equipment is that it is often necessary to assemble the component parts in jigs, in which case several operators may work on the same assembly simultaneously, or one operator may use two or more guns—each gun designed for certain parts.

Seam Welding.—Since seam welding, by its very nature, is a production operation, it must be classified as semi-automatic. Once the machine is set up, the operation consists merely of feeding work through the welding wheels. The set-up itself, however, is similar to set-ups on other types of machines and requires skill and experience. The actual feeding or operation requires dexterity on the part of the operator, even more so than in the case of spot and projection welding. This required skill consists primarily in guiding the work to produce straight and uniform seams.

Some types of work such as gasoline tanks and other containers permit the use of "Iron Man" work-support fixtures in which the work is automatically guided through the machine, thus reducing the required operating skill. In many cases the use of these fixtures permits one operator to operate two machines.

Butt Welding.—Butt-welding machines cover a greater range or variety of work than any other. They may be used for jobbing operations or for very high production, and the selection of the type of machine depends entirely on the over-all range of work (i.e., sizes, etc.) required of the machine, and the production expected.

For jobbing operations, even for a single weld, a flash-butt weld can be economically used. For all low production operations, the simplest type should be used—hand clamp, hand upset. This requires that the operator be an expert set-up man as well as a skilled operator. Of all resistance welding operations, more skill is required for hand flash welding than any other.

For higher production runs, economy dictates the substitution of air or hydraulic clamps and automatic (motor driven or hydraulic) upset mechanism. Automatic operation will not greatly increase the production, but does provide more uniform results and does eliminate the "fatigue" factor, which usually enters into hand operation.

Butt-welding machines can be furnished for general purpose work, or may be special machines for some particular application. In many cases tooling (dies, fixtures, locators, etc.) may constitute half the cost of the machine, in which case, it is of necessity a single-purpose machine, requiring a rebuilding operation to adapt it to some other job.

Other Forms of Resistance Welding.—There are many other forms of resistance welding which are of a more specialized nature, but should be mentioned, as:

Condenser discharge or stored energy welders are essentially spot welders, and may be considered in the same category.

Percussion welders may be similar to projection or butt welders, and impossible to definitely classify.

Pipe welders are essentially butt-seam welders involving extensive associated equipment.

In all of the foregoing, it has only been possible to outline very briefly the considerations in which labor costs and selection of equipment are involved. It is impossible to state even in general terms production estimates except for specific jobs. For instance, spot-welding machines can be built for operation at a rate of 300 spots per minute, but no such pro-

duction as that can be obtained because of the impossibility of handling at that speed.

The attainment of high operating speeds generally involves the use of automatic and special tooling features, all of which necessarily limit the general usefulness of the machine. It is, therefore, apparent that production speeds can be carried so far, beyond which the over-all economy may decrease.

Operating Power Cost

The actual cost of electric power used by resistance welding machines is a relatively simple matter to calculate, although the total cost of operation, i.e., the total amount paid for electric power, may not be so easily determined. Since some power companies have not given resistance welding loads serious consideration, rate structures vary widely with different companies.

Generally speaking electric power rates have four elements, any or all being used by the various power companies:

1. Power consumption in kwh.
2. Power factor.
3. Maximum demand.
4. Connected load.

These elements will be separately considered:

1. Power Consumption.—This element registers directly on the power watthour meter, and a few specific examples follow:

(*a*) *Spot Welder:* Assume a 50-kva. spot welder operating at 30 spots per minute, each spot of 10 cycles ($^1/_6$ sec.) duration; primary volts—440, "during weld" primary current 250 amp., power factor 50%.

From the above "during weld" kva. is 110, which at 50% power factor is 55 kw. Current flows 5 sec. each minute, or $^1/_{12}$ hr. each hour. Therefore, the kwh. consumption is 55 × $^1/_{12}$, or 4.6 kwh. per hour, which is about the same as that required by a 5-hp. motor. The percentage of the time current flows is usually expressed as duty cycle. In the above case, the duty cycle is $^1/_{12}$, or 8.33%.

(*b*) *Seam Welder:* Given a 100-kva. seam welder with primary "during weld demand" of 150 kva., 40% power factor, 50% duty cycle, then the kw. demand is 60 kw. and the power consumption is 30 kwh. per hour.

(*c*) *Flash Welder:* The "during weld" current of a flash welder is difficult to obtain from an indicating or recording meter due to the wave form distortion caused by the flashing. The only satisfactory method of obtaining power consumption on a flash welder is with a rotating standard kwh. meter. Lacking this, if the "during weld" current and power factor can be estimated, the actual power consumption can be calculated on the same basis as the preceding examples.

2. Power Factor.—Watthour meters for metering power consumption register volts × amperes × power factor, but the capacity of generating, transmission and distribution systems is measured in ampere capacity. Thus a machine whose power factor is 50% requires twice as much generating, transmission and distribution equipment as one whose power factor is 100%, and yet the watthour meter registration will be the same. For this reason, power companies frequently invoke a low power factor penalty or a high power factor premium, or both.

The power factor of resistance welding machines varies widely with various types. The power factor of short throat spot and press welders may be as high as 90%, while that for deep throat spot, press and seam welders may be as low as 20%.

Briefly, the power factor of a resistance welder is determined by the geometry or design of the secondary circuit. The longer the arms and the greater their separation, the lower the power factor will be. Roughly, the power factor is inversely proportional to the square root of the area of the secondary "loop." Thus, to secure the best power factor, the arms should be kept as short and close together as possible.

3. *Maximum Demand.*—This element is probably most widely used in power rate structures in supplementing the kwh. energy charge. Since a power company must have installed generating, transmission and distribution capacity to properly serve each customer, the actual kwh. rate is based upon this maximum demand. Maximum demands are usually integrated over 15- or 30-min. periods, consequently spot and flash welders do not usually have much effect on the maximum demand based on these periods, on account of the low duty cycle of these machines. Seam welders, having generally a much higher duty cycle, might contribute materially to this maximum demand.

Resistance welding equipment will usually contribute to the total demand charge of a plant to the extent of only 5% or 10% as much as the same electrical rating of motor equipment, and the increase in demand due to the welders can often be neglected when estimating power costs. Some power companies determine maximum demand on a kva. basis rather than a kw. basis, thus combining elements 2 and 3.

4. *Connected Load.*—Instead of measuring maximum demand, or in addition to it, some companies make a flat charge per month per hp. of connected load. Thus a resistance welder may be used only three months a year yet must pay a connected load charge throughout the entire year to compensate the power company for keeping idle equipment ready for the welder's use.

Until a resistance welding machine is of such a size at a given location as to be disturbing to other customers, i.e., cause flickering lights, some combination of the above four elements of power rates should prove adequate for the welding load along with the ordinary motor or power load. However, if the welding load proves to be disturbing, unless extra power facilities are provided for serving it, then these extra facilities must be paid for in some way. Thus, additional factors affecting power costs are introduced when it becomes necessary for the power company to provide new transmission and feeder cables, transformer substations or special welding service transformers at a cost out of proportion to the revenue to be derived. In such cases the consumer may either pay for part or all of the installation outright, or else pay a minimum or connected load charge based on the capacity provided.

It is very important for any prospective resistance welder user to make sure that his contemplated equipment can be properly served by the power company and that the cost of power will not be burdensome. He should always get in touch with the power company before any equipment is purchased.

Material Savings

One of the advantages in favor of resistance welding over other forms of fabrication is the elimination of filler rods, fluxes, rivets and other added materials. In the case of lap seam joints, the amount of material required for the lap is usually less than that required for other joints, as riveted or lock seam. Not only is the cost of rivets eliminated, but also the cost of drilling or punching rivet holes. Other methods of welding require filler rod, fluxes, etc., the cost of which has a definite bearing on the cost of the finished product.

The application of resistance welding has effected tremendous savings in the production of drills, taps, reamers and other perishable tools by welding high-speed tips to less expensive shanks. The same procedure is also carried out in the manufacture of axes, knives, shear blades and other similar tools.

Since resistance butt welds can be stamped, drawn or rolled the same as the parent metal, savings can often be effected by butt welding stamping and shearing scrap for fabrication into other parts. In some cases a small piece of steel (which may, in itself, be a piece of scrap) may be welded to a larger piece to produce an irregular stamping, thus reducing the amount of scrap from such a stamping.

Improvement in Product

The quality of resistance welding depends upon: (*a*) quality of appearance, and (*b*) physical quality.

Consumer demand for "streamlined" products extends to all industries with the result that pleasing appearance is one of the most important requisites of any product. Riveted joints are rapidly being discarded in favor of the smoother appearing spot, seam and flash welds. The latter present no bumps for the accumulation of dirt, grease, etc. While it is not always possible to produce spot welds without marks, under certain conditions invisible spot welds can be made and the finished product presents no trace of the weld. To accomplish this, however, it is usually necessary to do some buffing or polishing, although in most cases these polishing operations are required not alone for the welds but also for the surfaces on which the welds are made.

While invisible welds can be made, control of welding variables must be closely maintained. This means stricter supervision, better machines, tooling and controls. It is not necessary to provide invisible welds except on highly finished parts. If spot welds are neatly and uniformly spaced, they are at least as good appearing as rivets, and present no surface bumps.

Seam welds can be made practically invisible, but the demand for this is infrequent, and the cost may be considerably greater. Since seam welds are usually located on flanges or in close proximity to folded edges, it is usually possible for the designer to locate seam welds so that invisibility is not essential. As in spot welds, a straight seam weld, while readily visible, need not detract from the appearance of any product.

Butt-flash welds, probably more than any other type of resistance weld, are rendered invisible. The burr thrown up by the welding operation is

nearly always removed in two operations—trimming and grinding or polishing. Trimming is accomplished by hand chipping or machine trimming. This operation leaves a very slight ridge at the weld which is completely removed by grinding and polishing. Such highly finished products as automobile bodies, refrigerator cabinets, metal furniture have, for many years been butt-flash welded and all evidence of the weld completely eliminated.

As outlined earlier in this Chapter, since resistance welding employs no extraneous materials as filler rods, fluxes, etc., the metallurgy of the weld is not complicated by the addition of these materials. Since the welds are made under pressure, or forged, the original physical properties of the metals are less disturbed than by any other method.

Steels containing 0.2% carbon or more will be affected by any type of resistance weld (but less than by any other method). By proper heat treatment, however, the original properties may be restored.

Stainless steels may be spot, seam or butt welded without causing carbide precipitation, and with very little annealing at the weld.

Heat-treated aluminum alloys can be spot welded (but not seam or butt welded) without loss of the heat treatment. Seam and butt welding in heat-treated alloys should be avoided if the parts cannot be heat treated after welding.

Any type of resistance welding is performed with a minimum of warpage and distortion.

Capital Investment

As with any industrial process, the final cost of any resistance welding operation depends considerably upon the cost and installation of equipment required. The cost of the equipment, in turn, depends to a large extent on production requirements.

General purpose machines, i.e., machines suitable for a general line of work, should be amortized over a period of 5 to 15 yr., depending upon the type and extent of usage. Machines which are designed for a specific operation may be so special as to be virtually useless for any other purpose. In this case, the machine must be written off in the life of the job at hand. Many machines used in automotive production must be completely amortized in one year, or two at the most.

Costs of the simplest spot welders start at about $200 each, and continue upward. Resistance welder manufacturers have made substantial progress in the last few years toward standardization of types and sizes of standard machines, which has held the cost of these machines to a minimum. A single special machine or fixture and special tooling, as dies, locators, etc., must stand all engineering and development costs in addition to manufacturing costs. Therefore, this special tooling should be carefully analyzed from an economic standpoint.

Installation costs depend upon size and location. The largest item of installation is usually electric power feeders with protective equipment. Most machines require water service and pneumatic machines require compressed air.

C. ELECTRICAL CHARACTERISTICS OF RESISTANCE WELDERS

The rapid increase in the use of resistance welding during recent years has resulted in an enormous increase in the installed kva. capacity of resistance welding equipment. During the five-year period ending December 31, 1939, more than one and one-half million kva. of new welders have been installed in the United States alone, and it has been variously estimated that the present installed capacity of resistance welding equipment in the United States will total five to eight million kva. This five to eight million kva. nominal rating would represent a total maximum instantaneous demand in excess of 15 million kva. if all these machines were operated simultaneously. It becomes imperative, therefore, that the electrical components of these machines receive consideration and study by those interested in the art of resistance welding.

Only those components of the electrical system of the welder that are involved in the production and control of the welding current will be considered here, inasmuch as the electrical equipment employed for the mechanical and incidental functional operation of the welder is similar to the equipment employed in standard machine tool practice. The following discussion will apply basically to all resistance welding machines, and more specifically to spot welders and press welders, inasmuch as these two types of machines lend themselves more readily to a fundamental discussion of the electrical components.

The essential elements of a resistance welding machine for the production and control of the welding current may be listed as follows:

1. Primary contactor.
2. Welding timer.
3. Welding current adjuster.
4. Welding transformer.
5. Secondary circuit.

Figure 1 illustrates these various components in diagram form. In Fig. 1, the contactor closes upon manipulation of the timer, thus connecting the primary of the welding transformer to the supply lines through the regulator, causing current to flow through the secondary loop—composed of the flexible bands, arms, electrode holders, electrode tips and the material to be welded—for a time duration depending upon the adjustments of the timer. Although Fig. 1 is essentially applicable to a spot welder, the various elements indicated are fundamental essentials of all resistance welding machines.

Primary Contactor and Timer

The primary contactor serves as the medium for initiating and stopping the flow of the welding current under the control of the welding timer by connecting and disconnecting the welding transformer primary and the power supply system. Both the contactor and timer are available in various forms and in many combinations with each other, permitting the selection of a combination that will be suitable for every welding problem. The importance of these two elements and the many variations of the avail-

able apparatus dictates a thorough consideration and these two elements are, therefore, discussed in detail in Chapter 11.

Welding Transformers

The nature of resistance welding requires the application of an electric current of several thousand amperes for the welding of thin material and several hundred thousand amperes for very heavy welding. Fortunately, in a well-designed resistance welding machine, these currents may be

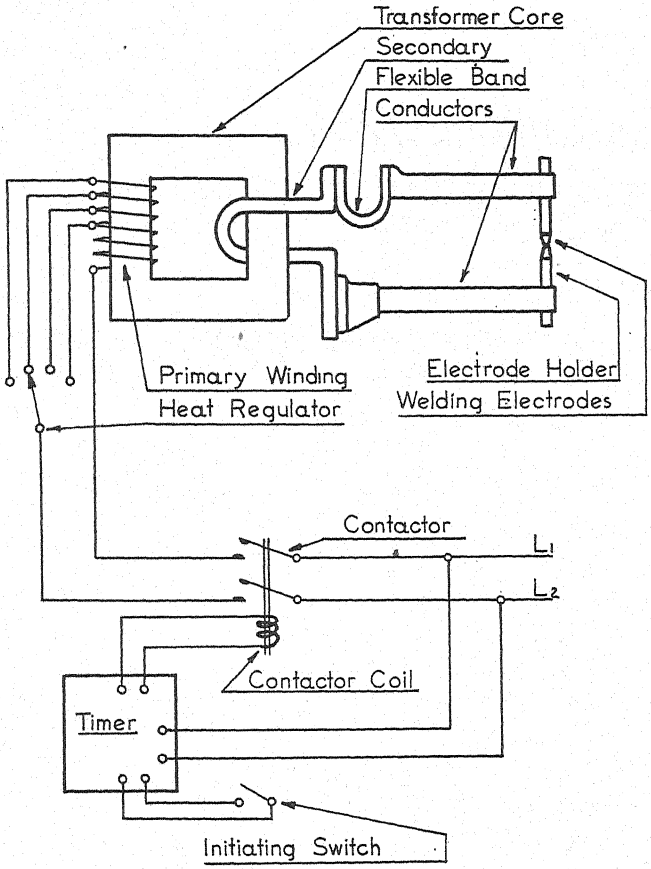


Fig. 1—Diagrammatic Representation of the Fundamental Electrical Components Usually Employed in Resistance Welding Machines

obtained with low voltages which seldom exceed 30 volts. It is the function of the resistance welding transformer to convert or transform the available commercial voltage, low current power to the required low voltage, high current power.

The fundamental theory of the welding transformer is similar to the theory applied to the conventional power transformer and will not, therefore, be discussed here.

The welding transformer differs, however, from the conventional power transformer in constructional details and in the manner in which it is operated. Whereas, the power transformer operates continuously at an almost constant load within its normal rating, the welder transformer must operate at rapidly recurring, intermittent overloads as high as 600% of its rating. This severe duty requires an extremely rigid and compact construction that is capable of withstanding the large mechanical forces existing within the transformer under these severe overloads. The large secondary current

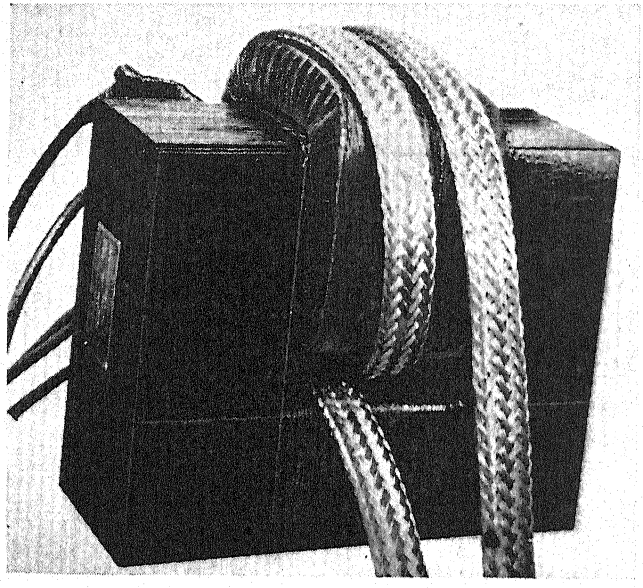


Fig. 2—Assembled Laminated Core and Primary Winding Adaptable for Use with Cable, Flexible Band, or Tubular Type Secondary. Flexible Cable Type Illustrated

and low voltage require a large cross-sectional area of secondary winding of only one or two effective turns and the required concentration of this large current necessitates a compact construction.

The various types of construction used in resistance welding transformers can be classified with respect to the construction of the secondary winding as follows:

1. Flexible secondary.
2. Air-cooled, rolled or cast copper secondary.
3. Water-cooled tubular secondary.
4. Water-cooled rolled or cast copper secondary.

The flexible secondary is seldom used in transformers larger than 50 kva., inasmuch as they are usually air cooled and do not lend themselves readily to adequate bracing of the transformer windings. The primary winding of these transformers can be wound directly on the iron core as illustrated by

the photograph in Fig. 2, which also illustrates the flexible cable type secondary.

The rolled or cast copper type of welding transformer secondary employing the "pancake" type of construction is generally used for transformers above 20 kva. In this type of construction, the primary winding is built in the form of several narrow discs or "pancakes," each of which is seldom more than $1^1/_2$ in. thick with the single turn cast or fabricated secondary winding of similar dimensions. The primary and secondary windings are then interleaved and placed on the laminated silicon steel core, with proper mechanical bracing to prevent relative movement between the primary windings, secondary windings and the iron core (see Fig. 3).

Transformer Ratings

The operation of a welding transformer differs from that of a conven-

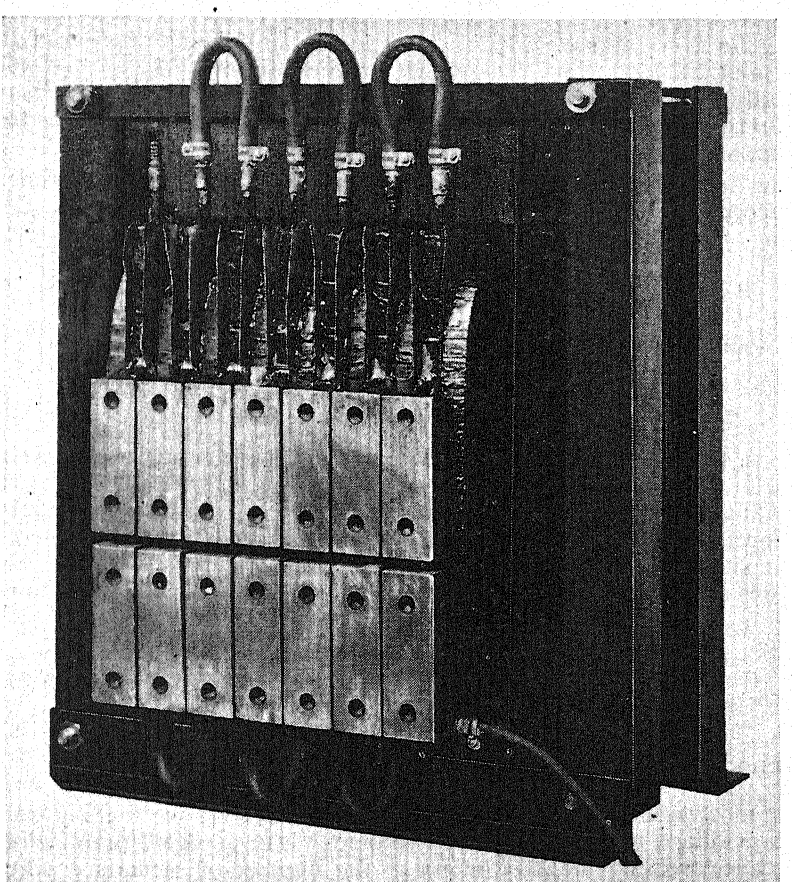


Fig. 3—Front View of a Completed 800-Kva. Transformer Showing the Secondary Terminal Pads and the Cooling Water Connections

tional power transformer in that the load on the power transformer is of a continuous nature, whereas the load on a welding transformer is a rapidly recurring one, usually in excess of its kva. rating. In order to obtain a closer agreement between the actual instantaneous kva. demand on a welder transformer and its kva. rating, the rating of the welding transformer is based on a 50% duty cycle instead of the continuous 100% duty cycle rating used for power transformers.

Since the kva. rating of a transformer specifies the kva. load which it can carry at its rated duty cycle without exceeding a specified temperature rise, the rating is thus determined by the rate at which the internally generated heat can be dissipated through its cooling system. The rate at which heat is generated within the transformer increases very rapidly as the transformer is overloaded and, in order to limit the amount of heat generated under overloaded conditions, it is necessary to limit the time that the transformer is actually carrying current by decreasing the operating duty cycle of the transformer. For example, consider a 100-kva. transformer rated at 50% duty cycle. This transformer could supply 100 kva. to a welder for 10 sec. in every 20 sec. (50% duty cycle) for an indefinite period of time. The same 100 kva. transformer, however, could supply 200 kva. to a welder for only 2.5 sec. in every 20 sec. ($12^1/_2$% duty cycle) without overheating due to the very rapid rate at which heat is generated internally in the transformer at that load.

The duty cycle of a transformer is defined as the percentage of time the transformer is actually carrying current and may be expressed by the following formula:

$$\text{Per cent duty cycle} = \frac{\text{Current "on" time}}{\text{Current "on" time} + \text{Current "off" time}} \times 100 \quad (1)$$

It is sometimes convenient to use the above formula in the following form:

$$\text{Per cent duty cycle} = \frac{\text{Cycles "on"}}{\text{Cycles "on"} + \text{Cycles "off"}} \times 100 \quad (2)$$

It is often necessary to find the permissible kva. output of a welding transformer while operating at a certain duty cycle, or to find the permissible duty cycle at which a welding transformer can operate while supplying a known kva. demand. These can both be easily found with the use of the curve shown in Fig. 4 which gives the per cent load which is allowable at various duty cycles. An illustration of the use of the curve is as follows:

> Assume a 500-kva. 50% duty cycle welding transformer supplying a 1500-kva. load. It is desired to find the maximum duty cycle at which this transformer can be safely operated. The per cent load, in this case, is 300% and on the curve a duty cycle of 5.5% is shown corresponding to this per cent load.

Methods of Regulating the Secondary Current

On most welders, provisions are made for regulating the welding current by providing a range of secondary voltages. The accepted practice in the resistance welding industry refers to the number of secondary voltages available on a welding transformer as "points of heat" and the tap switch as the "heat regulator." Several methods which are used to provide a range of secondary voltages are listed as follows:

1. Series resistor or series reactor.
2. Welding transformers with tapped primary windings or an auto transformer with tapped windings in conjunction with a welding transformer without taps.
3. Series-parallel coil connections.
4. Electronic heat control. (*See Heat Control, Chapter 11.*)

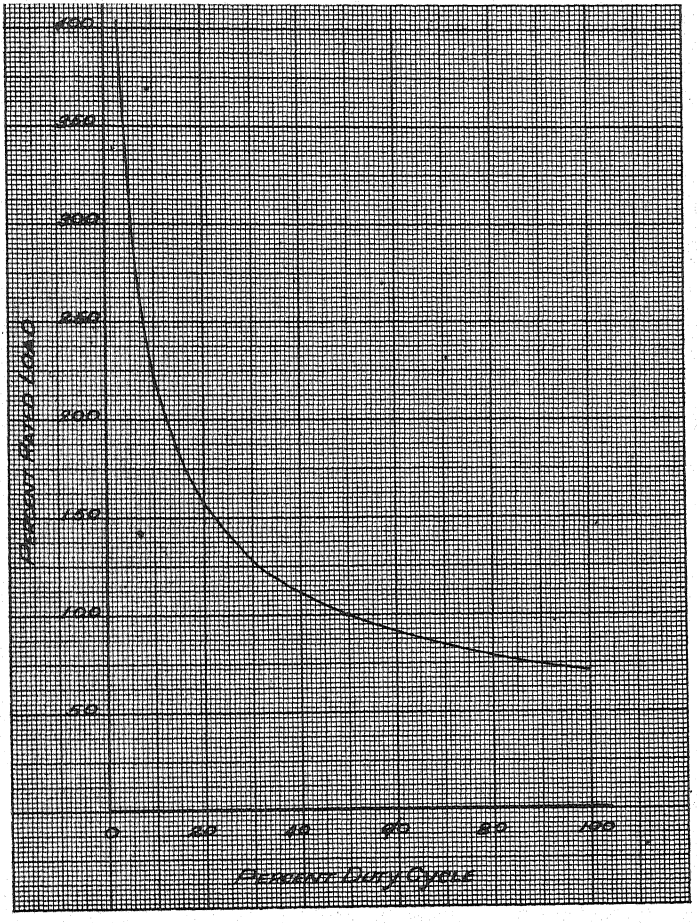


Fig. 4—Permissible Operating Duty Cycle Versus Per Cent of Nameplate Rating

The average operating range of most welders is near 300% rated load and 5% duty cycle.

Secondary Circuit

The secondary circuit or "welding loop" is usually considered as that portion of the welding machine having the fundamental function of conducting the high secondary current between the secondary terminals of the

welding transformer and the electrode tips. This secondary circuit is usually composed of the following elements:

1. Lower transformer connection between the transformer and the lower electrode holder.
2. Lower electrode holder.
3. Lower electrode tip.
4. Upper transformer connection between the transformer and the upper electrode holder.
5. Upper electrode holder.
6. Upper electrode tip.
7. Flexible conductor element to permit a relative movement between the upper and lower electrode holders.

These elements are common to all resistance welding machines, although the general form or application of the elements may vary greatly. They may also serve a mechanical as well as an electrical function as will be shown in the following chapters.

The secondary circuit, itself, is one of the major factors affecting the electrical performance in terms of the kva. demand required to deliver a given welding current. It will, therefore, be desirable to consider the electrical performance of the resistance welding machine in terms of the secondary circuit.

It was common practice in the earlier history of resistance welding to specify the welding ability of a resistance welding machine in terms of the transformer kva. rating. For example, the statement might be made that a 20-kva. machine was required to spot weld two pieces of No. 16 gage mild cold rolled steel. This statement was and is true only under certain very definitely specified conditions. In order to make this statement correct, it would be necessary to specify the time duration of current flow, the welding pressure, the contour of the electrode tips, the contour of the two pieces of steel and the geometry of the secondary circuit. If it is assumed that the statement is based upon accepted resistance welding technique, the first three items—namely, time, pressure and electrode tip contour—might be eliminated on the basis of common knowledge.

The contour and shape of the parts to be welded dictate the clearances which must be provided in the secondary circuit. The distance of the weld from the edge of the work will determine the unobstructed distance between the face of the machine and the electrode tips. This distance is termed "throat depth." The presence of vertical angles or contours will determine the separation of the arms, or "throat opening."

If, for example, a weld is required in the center of an open 12-in. cubical box, a 7-in. throat depth and a 13-in. throat opening will be required to allow for a 1-in. clearance. If, however, a weld is required in the center of two 12-in. square sheets, the throat depth would remain at 7 in. but the throat opening (or throat spacing) would probably be decreased to about 3 in. or 4 in. Assuming the thickness of the material to be the same in both examples, then the kva. demand required to perform a weld in the box will be approximately 175% of the kva. demand required to perform the same weld on the two flat sheets.

It is evident from the foregoing that the electrical ability to perform a

given weld cannot be expressed in terms of kva. without definite specifications relative to the machine itself, with particular reference to the secondary circuit.

There is one and only one basic index to the welding ability of a resistance welding machine in terms of the electrical ability to perform a given welding job. That index is secondary current. We can definitely state that the maximum secondary current which a welding machine will deliver at the weld is the true measure of the welding ability of the machine in so far as the electrical characteristics are concerned.

In the preceding statement, a rather fine but necessary distinction has been drawn between the electrical "ability" and the electrical "capacity" of the machine. By "ability" is meant the electrical competency of the machine to perform any one given weld and refers only to the instantaneous output of the electrical equipment. By electrical "capacity" is meant the thermal competency of the machine to perform a given number of welds in a specified time without exceeding the specified temperature limits of the various component parts of the electrical equipment.

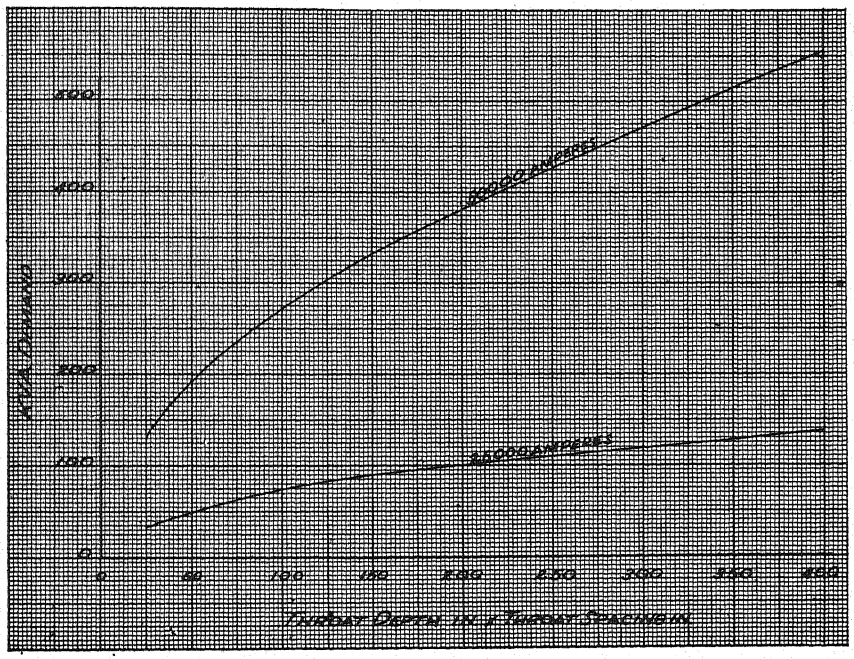


Fig. 5—Instantaneous Kva. Demand Required for 25,000 and 50,000 Secondary Amperes with a Change in Throat Dimensions

The product of the throat depth and throat spacing is used for simplification.

Figure 5 illustrates the increase in the instantaneous kva. demand required by a welder with an increase in size of the secondary loop to produce a given secondary current. For simplicity, the throat depth and the throat opening have been plotted as a product of the two, giving the area in

square inches enclosed by the secondary circuit. An examination of the curve will indicate that the kva. required is closely proportional to the square root of the enclosed area. This is only approximately true as this proportion will vary with the ratio of the throat depth to the throat spacing; consequently, the information contained in Fig. 5 should be used for comparative purposes only.

Figure 5 also illustrates quite clearly the importance of selecting a welding machine with the smallest throat depth and throat opening that is permitted by the particular welding problem at hand. There is a tendency to provide a large throat for possible future requirements, but usually these future requirements for a larger throat machine do not materialize before increased production and the increased use of resistance welding has necessitated the installation of an additional machine.

It is also important in the selection of a welding machine to choose a machine of ample kva. rating rather than select a machine which must always operate at its maximum capacity. Frequently, it is assumed that the smaller kva. machine will require a smaller kva. demand from the power supply line in performing a given weld.

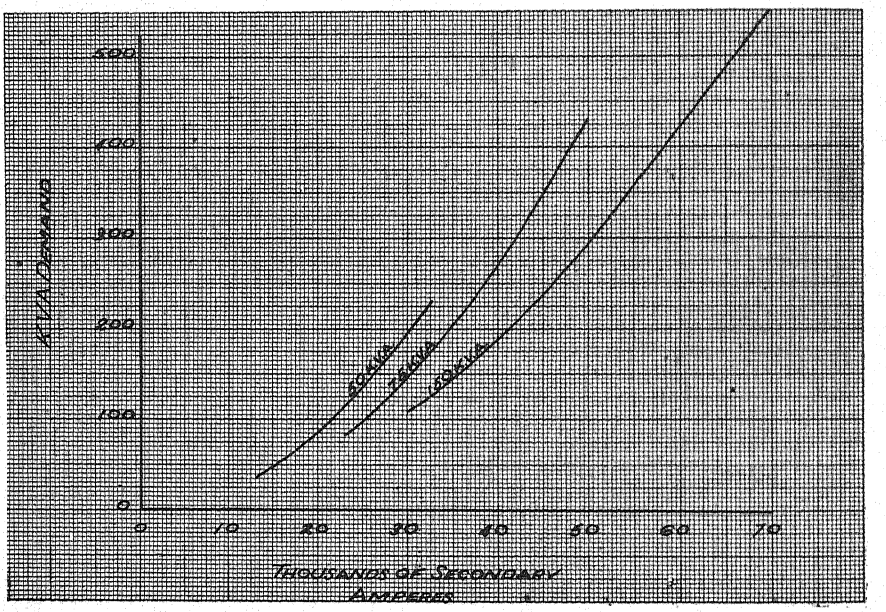


Fig. 6—Kva. Demand Required by Different Sizes of Welding Machines to Obtain Various Secondary Current Outputs

These values are for a series of press type welders but also illustrate the general characteristics for other types of resistance welding machines.

Exactly the opposite is true, however, as can be seen in Fig. 6 which shows a curve of welding current vs. kva. demand during weld for several kva. ratings of machines.

Figure 7 illustrates an additional advantage in the selection of a machine of ample kva. rating. This curve shows the increase in the permis-

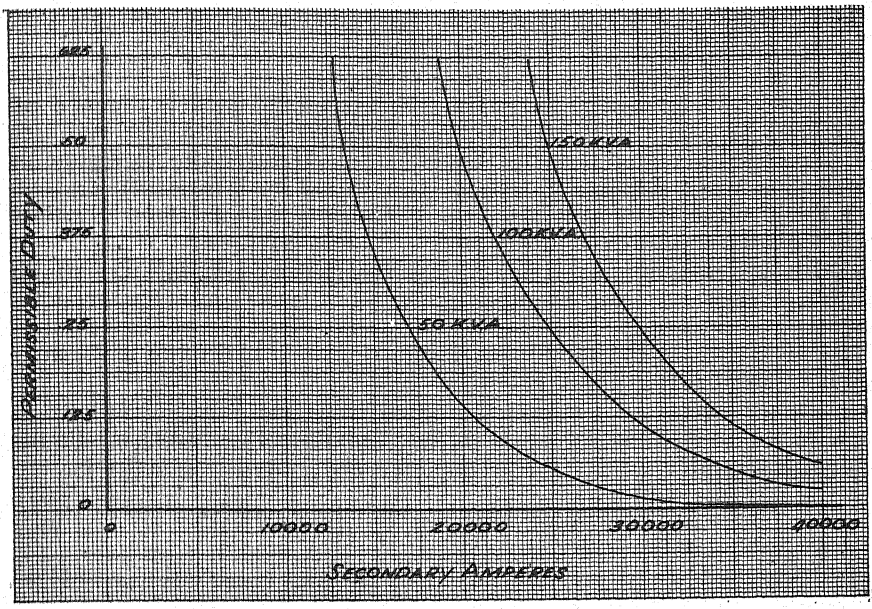


Fig. 7—A Comparison of Permissible Duty Cycle Between Machines of Different Kva. Ratings

The basis for selecting the proper machine kva. rating at a specified duty cycle and secondary current is also illustrated by these curves.

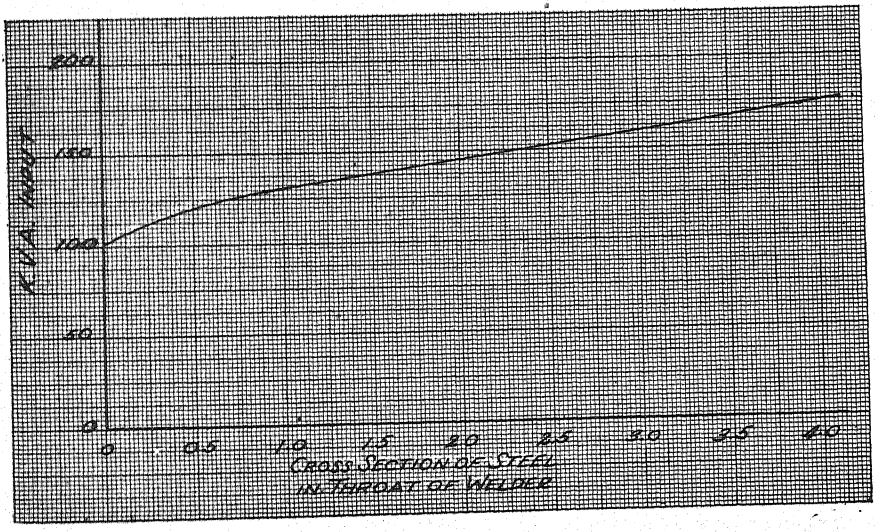


Fig. 8—Increase in Kva. Required to Compensate for the Introduction of Magnetic Material in the Throat of a Welder

This effect varies with the type of machine and the length-width ratio of the magnetic material cross-section.

sible duty cycle of the electrical equipment obtainable with a larger kva. rating for a given secondary current output.

The effect of magnetic material in the throat of the machine is illustrated in Fig. 8 which shows the increase in the instantaneous kva. demand required to perform a given weld with an increase in the cross-sectional area of the magnetic material in the throat. This effect may be negligible for the majority of welding applications but must not be disregarded in selecting the kva. capacity of the machine. This curve is based upon a definite set of conditions and cannot be used for estimating purposes.

With the maximum secondary current specified at some definite throat depth and throat spacing, the welding *ability* of the electrical components is definitely established. To establish the welding *capacity* of the machine, it is only necessary to specify one additional factor; that factor is the duty cycle of the welding operation itself.

The duty cycle, as previously explained, is the ratio of time of current flow to the total elapsed time from the beginning of one weld to the beginning of another weld. The formula usually applied in practice is:

$$\text{Duty cycle} = \frac{\text{Welds per minute} \times \text{Current "on" cycles per weld}}{3600 \text{ (cycles per min.)}} \qquad (3)$$

The following data were obtained from an oscillogram record of a modern high-speed automatic welder:

(1)	Cycles per weld	4
(2)	Total number of welds per assembly	12
(3)	Total time for 12 welds	120 cycles
(4)	Time interval between welds	6 cycles
(5)	Total time per weld	10 cycles
(6)	Secondary amperes	18,000
(7)	Open circuit secondary volts	6
(8)	Welds per minute maximum	360
(9)	Assemblies per hour	600
(10)	Total average welds per hour	7200

Two duty cycles will be computed in the following examples. The first duty cycle is the maximum short time duty cycle necessary in selecting the line contactor. The second duty cycle is the one hour average or sustained duty cycle necessary in selecting the welder transformer, power transformer and the power supply lines. The welding transformer has been computed for both duty cycles to serve as a comparison.

Applying this information to Formula 3, we have:

$$\text{Duty cycle} = \frac{360 \times 4}{3600} = 0.40 \text{ or } 40\% \text{ duty cycle}$$

The maximum instantaneous kva. demand required for the weld would be:

$$\text{Kva. demand during weld} = \frac{\text{Open circuit secondary volts} \times \text{Secondary amperes}}{1000} \qquad (4)$$

$$\text{Kva. demand during weld} = \frac{6 \times 18{,}000}{1000} = 108 \text{ kva.}$$

In order to determine the nominal 50% duty cycle kva. rating of the welding transformer, we can make use of the following formula:

$$\text{Welder transformer kva. rating} = \frac{\text{kva. demand during weld} \times}{\sqrt{2 \times \text{Duty cycle}}} \qquad (5)$$

Welder transformer kva. rating = $108 \times \sqrt{2 \times 0.40} = 96.4$ kva. at 50% duty cycle

This oscillogram record, however, covered only one operation of the machine, welding one complete assembly. Consideration must be given to the time required for the operator to load and unload the machine. The maximum production is 600 assemblies per hour, 12 welds per assembly, or 7200 welds per hour. Applying Formula 3, we find:

$$\text{Duty cycle} = \frac{7200}{60} \times \frac{4}{3600} = 0.133 \text{ or } 13.3\%$$

The nominal kva. welder transformer required under these conditions would then be:

Welder transformer kva. rating = $108 \times \sqrt{2 \times 0.133} = 55.9$ kva. at 50% duty cycles

Specification of Electrical Output

In consideration of the foregoing basic principles, the electrical performance of a welding machine may be definitely specified by stating the maximum secondary amperes required at a specified throat depth and throat opening when operated at a specified duty cycle.

The following sample clause will serve to illustrate this performance requirement:

> "The electrical equipment of the machine shall be capable of delivering 35,000 secondary amperes at the welding electrodes with a 30-in. throat depth and a 10-in throat opening at a duty cycle of 10% with rated line voltage at the primary terminals without any portion of the machine attaining a temperature which shall prove injurious to the continued operation of the machine."

D. POWER SUPPLY FOR RESISTANCE WELDING MACHINES

An adequate power supply is one of the major requisites of present day, high-production resistance welding. A major part of the power supply system for any industrial plant lies within the plant itself and consists of the power supply transformers and the power supply conductors.

In considering the installation of a resistance welding machine, it is necessary to determine the kva. rating of the power supply transformer required and the size of the power supply conductors. The power supply transformer which is usually connected to a 2300- or 4000-volt primary feeder is installed external to the machine and should not be confused with the welder transformer mounted in the welding machine. The power supply conductors are the power leads between the power supply transformer and the welding machine.

The selection of the power supply transformer and supply conductors is governed by two factors—the permissible voltage drop and the permissible heating. The permissible voltage drop is the determining factor in the majority of installations but consideration must be given to both factors. In all cases, the final selection of the equipment must be determined by that factor which requires the larger transformer and the larger conductors.

It is relatively simple to determine the size of the power transformer on

the basis of heating alone, inasmuch as the welder transformer is rated on a heating basis and a definite ratio exists between the two ratings. Power transformers are usually rated on a continuous or 100% duty cycle basis; whereas the welder transformer is rated on a 50% duty cycle basis, as previously explained. The power transformer rating required on a heating basis only for a given welding machine will, therefore, be equal to the welder transformer 50% duty cycle rating divided by the square root of two. The square root of two is the conversion factor.

$$\text{Power transformer rating (Heating basis only)} = \frac{\text{Welding transformer rating (50\% duty cycle)}}{\sqrt{2}} \qquad (6)$$

To find the size of the power transformer required on a heating basis for the proper operation of a 200-kva. seam welder, this value can be substituted in the above formula as follows:

$$\frac{\text{200 kva. (50\% duty cycle)}}{\sqrt{2}} = \text{141.4 kva.}$$

If there is more than a single machine to be served from a common power supply transformer, a thorough study of actual operating duty cycles of all machines and the operating diversity factor between machines must be made. In actual practice, most welding machines except some seam welders usually operate below their maximum thermal capacity because the size of the transformer in the machine is dictated by the required welding current output rather than by thermal considerations. Tests of many installations show that the values given in Table 1 are representative of actual field conditions. Thus, for instance, if the machines are predominately spot, projection or flash welders, a power supply transformer with a rating of 15% of the sum of the nameplate ratings of the machines would, in most cases, be adequate as far as permissible heating is concerned.

Table 1—Equivalent Continuous Loading of Typical Welding Machine Installations

Types of Welding	Equivalent Continuous Load Expressed in Per Cent of Sum of Nameplate Ratings
Spot, projection, flash	5 to 10% (most installations) 10 to 20% (very few installations)
Hydromatic, butt	10 to 20%
Seam	25 to 70%

In order to determine the size of the power supply transformer required to serve a welding machine on the basis of voltage drop, it will first be necessary to determine the maximum permissible voltage drop which can be tolerated. Where the same power transformer is used with two or more machines in such a manner that the voltage drop resulting from the operation of the one machine will be reflected in the operation of the second machine, it is advisable to confine the total maximum voltage drop to not more than 10% or, at the most, 15%. All voltage drops should be measured at the locations of the welder and the percentage voltage drop should be calculated by means of the following formula:

$$\frac{\text{No load voltage} - \text{Full load voltage}}{\text{No load voltage}} \times 100 = \text{Per cent voltage drop} \qquad (7)$$

Likewise, where an electronic tube-type timer and contactor is employed, it will be necessary to hold to this limitation of 15% unless provisions are made to maintain the control voltage to the electronic tube panel. Where an electronic tube-type contactor is employed on a 220-volt circuit, it will be necessary to limit the maximum voltage drop to 10% in order to insure consistent operation of the electronic tube-type contactor. It is generally considered good practice to stay within the 10% limit in all cases; however, if this is found to be difficult and the cost excessive, the upper limit of 15% may prove satisfactory.

The percentage of the total voltage drop that should be apportioned to the power transformer and the percentage apportioned to the supply leads between the transformer and the welding machine involve a consideration of installation costs as well as the amount of voltage drop existing in the high voltage system ahead of the transformer. In most cases, very little can be done toward reducing the voltage drop in the high-voltage system at a cost commensurate with the expenditure needed for the same percentage reduction in the low-voltage system. Where more than one welder is involved, the largest welder of the group is always considered when calculating voltage drop.

In the case of service from a power company, the amount of voltage drop in the high-voltage system for a given welding load is dependent upon the relative location of the industrial plant with respect to the power company's large distribution substations as well as generating stations. If the plant is in an established industrial area served by large substations and not too far from large generating stations, the voltage drop in the high-voltage system will be a negligible factor. However, if the plant has been located in a rural or small-town area far removed from the main generating stations, the high-voltage system regulation may loom up as a very troublesome factor. Any plant in which resistance welding is extensively used should carefully investigate this matter of high-voltage system regulation when contemplating moving the plant to any other location with less adequate power facilities for welding.

In the case of private power generation, the voltage drop at the generator bus will be inversely proportional to the total rating of all generators feeding the bus. The small and moderately sized plant will experience considerable difficulty in handling any but the smaller sized welding machines without encountering lamp flicker problems in their plant and office lighting.

The high-voltage system regulation can be obtained from the local power company by giving them the maximum kva. and power factor that the largest welding machine will draw from the power system. Subtract the figure obtained from the total allowable 10% or 15% voltage drop and the remainder is that which can be allowed in the stepdown bank and secondary or low-voltage bus system.

A group of welders can be served either from a single-phase transformer bank or a three-phase bank, and where the welding load is large enough to justify a separate transformer bank for welding load only, it will be found advantageous and more economical of capacity to use a single-phase system. The load is single phase and it will remain single phase no matter how the transformers ahead of it are connected. Sometimes it is desirable to spread the individual single-phase loads over the three-phase wires for more

economical utilization of the supply lines, but unless there are large numbers of machines connected, the necessity for balancing the load is not important. When there are many machines, they are usually scattered around in different parts of the plant so that several stepdown banks become necessary at different locations. In this case, individual single-phase banks can be connected to separate phases and thus bring about some semblance of balance on the supply wires.

A given kva. of single-phase load fed from a three-phase transformer bank will cause just twice as much transformer voltage drop as the same kva. load fed from the same capacity in transformers connected as a single-phase bank. It is thus obvious that, where the transformer voltage drop must be kept at a minimum, it is highly desirable and more economical to use single-phase, stepdown banks of transformers.

The voltage drop through the power transformer is a function of a characteristic called "transformer impedance." This transformer impedance is a measure of the total restriction which the transformer offers to the flow of current and is usually expressed as a percentage of the rated voltage. The impedance value for standard power transformers is generally between 5% and 6% and is stamped upon the transformer nameplate. For the purpose of this discussion, this value can be interpreted as the percentage voltage drop through the transformer when rated kva. load is applied. For example, a 200-kva. power transformer with a nameplate stamping of 5% impedance will have a 5% voltage drop at 200 kva., a 10% voltage drop at 400 kva., a 15% voltage drop at 600 kva., etc.

While the foregoing explanation is subject to correction for technical accuracy, the approximations indicated are sufficiently accurate in estimating the size of the power transformer required for supplying a given, during-weld kva. demand with a given maximum voltage drop through the power transformer.

The selection and design of supply conductors or bus system between the power transformers and the welding machines depend somewhat upon their relative locations. If separate conductors are used for each machine, they should be of such size and spacing to limit the voltage drop to about 5 or 10%. If a common cable or bus system is used for several machines, then the voltage drop allowed in the conductors must be added to that allowed in the high-voltage system and transformers and the total drop kept within the previously discussed limit of 10 or 15%.

The selection of the supply cable size is complicated by the necessity of considering the length of the cable run, the duty cycle and the primary voltage of the welding transformer. In view of these complications, Tables 2, 3, 4 and 5 have been prepared from which the proper size individual cable feeders can be obtained for the usual distances encountered and the most commonly used current values.

In compiling these tables, the rules of the American Institute of Electrical Engineers governing maximum allowable copper temperature have been followed and the following assumptions have been made:

1. The cables are installed in free air, the ambient temperature of which is 40°C. These tables do not cover the case of cables in ducts or conduit, except for Table 5.

2. The tables cover single circuits and it is assumed that the circuits are

Table 2—Cable for Use with Resistance Welding Machines for 440 Volts, Single-Phase Circuit Based on 5% Regulation—75°C. Copper—40°C. Ambient

During Weld Current, Amp.	One-Conductor Cables Spaced 4 In. and 5 In. Apart Conductor Size AWG or MCM					
	Distance from Supply Transformer to Welder, Ft.					
	50	100	150	200	300	400
	5% Duty Cycle					
100	8	8	8 [b]	6	4	2
250	8	4	2	1	0	000
500	2	2	0	000	400	800
750	0	0	0000	400	1500	2500-*a*
1000	00	000	400	800	2500-*a*	
1500	250	400	1500	2500-*a*		
2000	400	800	2500-*a*			
2500	600	2000				
3000	800	2500-*a*				
3500	1000					
4000	1250					
4500	1500					
5000	2000					
5500	2250-*a*					
6000	2500-*a*					
6500	3000-*a* [c]					
	10% Duty Cycle					
100	8	8	8 [b]	6	4	2
250	4	4	2	1	0	000
500	1	1	0	000	400	800
750	000	000	0000	400	1500	2500-*a*
1000	250	250	400	800	2500-*a*	
1500	500	500	1500	2500-*a*		
2000	700	800	2500-*a*			
2500	1000	2000				
3000	1500	2500-*a*				
3500	1750					
4000	1750-*a*					
4500	2000-*a*					
5000	2500-*a*					
5500	2750-*a*					
6000	3000-*a* [c]					
	30% Duty Cycle					
100	8	8	8 [b]	6	4	2
250	1	1	1	1	0	000
500	0000	0000	0000	0000	400	800
750	400	400	400	400	1500	2500-*a*
1000	600	600	600	800	2500-*a*	
1500	1250	1250	1500	2500-*a*		
2000	1750	1750	2500-*a*			
2500	2000-*a*	2000-*a*				
3000	2500-*a*	2500-*a* [c]				

Table 2—(*Continued*)

During Weld Current, Amp.	One-Conductor Cables Spaced 4 In. and 5 In. Apart Conductor Size AWG or MCM					
	Distance from Supply Transformer to Welder, Ft.					
	50	100	150	200	300	400
	70% Duty Cycle					
						b
100	4	4	4	4	4	2
250	00	00	00	00	00	000
500	400	400	400	400	400	800
750	700	700	700	700	1500	2500-*a*
1000	1250	1250	1250	1250	2500-*a*	
1500	1750-*a*	1750-*a*	1750-*a*	2500-*a*		
2000	2800-*a*	2800-*a*	2800-*a*			
				c		

NOTE: (*a*) Means annular cable. All others standard strand.
(*b*) Ratings to the left of the vertical line are based on heating.
(*c*) Ratings to the right of the vertical line are based on regulation.

single phase, each circuit consisting of two cables installed in a horizontal plane. Where more than two cables are needed to carry the load, two or more circuits may be used.

3. These tables refer only to single-conductor cables. Where heating is the governing factor, it is assumed that standard-strand cables will be spaced 4 in. center to center and that annular cables will be spaced 5 in. center to center. In Table 3, it is assumed that the cables are in contact and in Table 5, the cables are in conduit.

4. Tables are based on duty cycles of 5, 10, 30 and 70%, the averaging time being not in excess of 1 min.

5. The tables are based on single-phase, 440-volt, 60-cycle circuits, the voltage drop being not in excess of 5% and copper temperatures not in excess of 75°C. It is assumed that the load cycles will follow one another continuously.

6. The rms. current given is the primary current during the weld.

7. Where lead sheaths are used, it is assumed that all single conductor cables will be operated with open-circuited sheaths; i.e., sheaths bonded and grounded at one point only.

8. It is assumed that the cable will be so installed that it is not in close proximity to large masses of magnetic materials.

In order to use these tables for a 220-volt, 60-cycle supply, it will only be necessary to multiply the actual distance from the supply transformer to the welder by a factor of 2 when selecting the cable from the tables. For example, if the actual distance is 200 ft., the cable should be selected on the basis of 400 ft. and the column headed "400 ft." in the tabulation must be used.

For example, in the use of these tables, the individual cable size for a press welder will be selected as follows. The basis of our example will be a 100-kva. press welder, 440 volts, 60 cycles, single phase, having a maximum demand of 400 kva., or 910 primary amp., operating on a duty cycle of 3% with the welder located 100 ft. from the power supply transformer. A voltage drop of 5% in the supply cables is assumed and we shall further assume that these cables will be installed with a 4-in. center distance between cables.

Table 3—Cable for Use with Resistance Welding Machines for 440 Volts, Single-Phase Circuit Based on 5% Regulation—75°C. Copper—40°C. Ambient

During Weld Current, Amp.	One-Conductor Cables in Contact Conductor Size AWG or MCM					
	Distance from Supply Transformer to Welder, Ft.					
	50	100	150	200	300	400
	5% Duty Cycle					
100	8	8	8 *b*	6	4	3
250	6	4	2	1	0	00
500	2	2	0	00	0000	300
750	0	0	000	0000	350	600
1000	000	000	0000	300	600	1500-*a*
1500	300	300	350	600	2250-*a*	
2000	500	500	600	1500-*a*		
2500	700	700	1500	3000-*a*		
3000	1000	1000	3000-*a*			
3500	1250	1250				
4000	1500	1500-*a*				
4500	2000	2250-*a*				
5000	2000-*a*	3000-*a*				
5500	2500-*a*					
		c				
	10% Duty Cycle					
100	6	6	6	6 *b*	4	3
250	2	2	2	1	0	00
500	0	0	0	00	0000	300
750	000	000	000	0000	350	600
1000	300	300	300	300	600	1500-*a*
1500	500	500	500	600	2250-*a*	
2000	800	800	800	1500-*a*		
2500	1250	1250	1500	3000-*a*		
3000	1750	1750	3000-*a*			
3500	2000-*a*	2000-*a*				
4000	2500-*a*	2500-*a*				
			c			
	30% Duty Cycle					
100	6	6	6	6	4 *b*	3
250	00	00	00	00	00	00
500	0000	0000	0000	0000	0000	300
750	400	400	400	400	400	600
1000	600	600	600	600	600	1500-*a*
1500	1250	1250	1250	1250	2250-*a*	
2000	2000-*a*	2000-*a*	2000-*a*	2000-*a*		
				c		
	70% Duty Cycle					
100	2	2	2	2	2	2 *b*
250	000	000	000	000	000	000
500	400	400	400	400	400	400
750	800	800	800	800	800	800
1000	1500	1500	1500	1500	1500	1500-*a*
1500	2500-*a*	2500-*a*	2500-*a*	2500-*a*	2500-*a*	
					c	

NOTES: (*a*) Means annular cable. All others standard strand.
(*b*) Ratings to the left of the vertical line are based on heating.
(*c*) Ratings to the right of the vertical line are based on regulation.

Referring to Table 2 under the tabulation for 5% duty cycle, and selecting the 1000-amp. horizontal line under the "During Weld Current Amperes" and proceeding horizontally to the 100-ft. column, we find that No. 000 cable is required. It should be noted that the cable size would have been increased to 400,000 circular mils if the distance between the welder and the power supply transformer had been increased to 150 ft. and the selection of the cable in both instances would have been governed primarily by the voltage drop.

If this welder were to be operated on 220 volts, the other conditions remaining the same, the "During Weld Current Amperes" would be 1820 amp. Again consulting Table 2 and selecting the horizontal line of 2000 amp. in the first column under 5% duty cycle and reading horizontally to the right, it would now be necessary to proceed to the 200-ft. column inasmuch as the distances must be doubled when using these tables for 220 volts. Since a blank space occurs in the 200-ft. column opposite 2000 amp., it can be assumed that this arrangement is not recommended. The next solution would be the installation of two parallel circuits, each carrying 1000 amps.

A further reference to the table shows a recommendation of 800,000 circular mil cable under the 200-ft. column opposite the 1000 amp. The recommended cable run for supplying this welder under the conditions outlined in the example with a 220-volt power supply would thus necessitate two parallel circuits, each composed of 800,000 circular mil cable.

Another solution for the 220-volt supply cables can be obtained from Table 3. In this table, we find under the 200-ft. column and opposite the 2000 amp., that one and one-half million circular mil annular cable would be required. Another solution would be two parallel circuits of 300,000 circular mil cable as indicated under the 200-ft. column opposite the 1000 amp. Still another solution would be the 600,000 circular mil concentric cable of Table 4.

All of the foregoing solutions are based upon the 100-kva. press welder having its own supply cables. In case a large group of welders are served from a common supply cable or bus system and assuming that from our previous example we have an allowable 4% drop remaining for the bus system, Figs. 9 and 10 can be used in the selection of the proper cable or bus. Assuming that the bus must be 400 ft. long, the two $^1/_4$-in. × 4-in. coppers on $2^1/_4$-in. centers (Fig. 10) would handle 1000 amp. with about 4% voltage drop. A study of actual operating duty cycles and loads of all the welders must be made in order to be sure that an adequate cross-section of copper is provided from a heating standpoint.

The low-voltage bus or feeder from the transformer to the welders should always be as short as possible and of low reactance design in order to keep the voltage drop within the prescribed limits. Probably the simplest and cheapest bus construction consists of insulated wire, taped together and either hung on racks or pulled in conduit (Fig. 9). One disadvantage of such construction is the lack of facilities for easily tapping off connections for welders throughout the bus length. When only two or three welders are to be served at a common location at considerable distance from the supply transformer this construction is cheap and effective.

A bus construction which permits easy tap connections at frequent in-

Table 4—Cable for Use with Resistance Welding Machines for 440 Volts, Single-Phase Circuit Based on 5% Regulation—75°C. Copper—40°C. Ambient at Load Power Factor, Giving Maximum Voltage Drop

During Weld Current, Amp.	Two-Conductor 600-V. Concentric Cable Conductor Size AWG or MCM					
	Distance from Supply Transformer to Welder, Ft.					
	50	100	150	200	300	400
			5% Duty Cycle			
			b			
100	8	8	6	6	4	2
250	6	4	2	2	2	00
500	1	1	1	00	000	250
750	00	00	00	0000	300	400
1000	0000	0000	0000	250	400	500
1500	350	350	350	400	600	800
2000	600	600	600	600	700	1250
2500	800	800	800	800	1000	1750
3000	1250	1250	1250	1250	1500	2500
3500	1500	1500	1500	1500	2000	
4000	1750	1750	1750	1750	2500	
4500	2250	2250	2250	2250	3000	
5000	2750	2750	2750	2750		
5500	3000	3000	3000	3000		
				c		
			10% Duty Cycle			
			b			
100	8	8	6	6	4	2
250	4	4	2	2	2	00
500	0	0	0	00	000	250
750	0000	0000	0000	0000	300	400
1000	350	350	350	350	400	500
1500	700	700	700	700	700	800
2000	1000	1000	1000	1000	1000	1250
2500	1500	1500	1500	1500	1500	1750
3000	2000	2000	2000	2000	2000	2500
3500	2500	2500	2500	2500	2500	
4000	3000	3000	3000	3000	3000	
					c	
			30% Duty Cycle			
					b	
100	6	6	6	6	4	2
250	1	1	1	1	1	00
500	250	250	250	250	250	250
750	500	500	500	500	500	500
1000	800	800	800	800	800	800
1500	1750	1750	1750	1750	1750	1750
2000	2500	2500	2500	2500	2500	2500
						c
			70% Duty Cycle			
					b	
100	4	4	4	4	4	2
250	000	000	000	000	000	000
500	500	500	500	500	500	500
750	1000	1000	1000	1000	1000	1000
1000	1500	1500	1500	1500	1500	1500
1500	3000	3000	3000	3000	3000	3000
						c

Note: (*b*) Ratings to the left of the vertical line are based on heating.
(*c*) Ratings to the right of the vertical line are based on regulation.

tervals along its length is desired in production plants where manufacturing layouts are continually changing. With the welder bus extending the full length of the plant, welders can be moved about to meet the changing conditions without great trouble. The bus can be made up on the job or it can be purchased, prefabricated in unit lengths, either with or without enclosures. The copper spacing should be kept at a minimum. There are several standard designs of busses offered by different manufacturers particularly for welding loads.

Table 5—Feeder Cable Sizes for Resistance Welding Machines for 440 Volts, 60-Cycle, Single-Phase Circuit Based on 5% Voltage Drop in Cable When Load Is Applied—85°C. Copper—40°C. Ambient—30 to 40% Power Factor Load Only Cable Installed in Conduit

During Weld Current, Amp.	Two-Conductor Concentric Cable Conductor Size AWG or MCM — Distance from Supply Transformer to Welder, Ft. 50	100	150	200	300	400
			5% Duty Cycle			
					b	
100	8	8	8	8	6	6
250	6	6	6	4	2	2
500	2	2	2	2	0	00
750	00	00	00	00	000	0000
1000	0000	0000	0000	0000	0000	300
1500	400	400	400	400	400	500
2000	700	700	700	700	700	800
2500	1000	1000	1000	1000	1000	1250
3000	1500	1500	1500	1500	1500	2000
3500	2000	2000	2000	2000	2000	3000
4000	2500					
						c
			10% Duty Cycle			
					b	
100	8	8	8	8	6	6
250	4	4	4	4	2	2
500	00	00	00	00	00	00
750	250	250	250	250	250	250
1000	400	400	400	400	400	400
1500	750	750	750	750	750	750
2000	1250	1250	1250	1250	1250	1250
2500	2000	2000	2000	2000	2000	2000
						c

During Weld Current, Amp.	Two-Conductor Concentric Cable Conductor Size AWG or MCM All Distances 50–400 Ft., Inclusive	
	30% Duty Cycle	*70% Duty Cycle*
100	6	2
250	0	0000
500	300	600
750	600	1250
1000	1000	2500
1500	2500	

NOTE: (*b*) Ratings to the left of the vertical line are based on heating.
(*c*) Ratings to the right of the vertical line are based on regulation.

By dividing the supply system into the three parts: (1) high voltage system, (2) power transformer and (3) low voltage feeder or bus, and providing a balanced layout so that the sum of the voltage drops in the three parts does not exceed the predetermined allowable standard, an adequate power supply is assured. For a more complete discussion of power supply layouts for welder installations, see A.I.E.E. Subcommittee on "Power Supply for Welding Operations. Report III. Factory Wiring for Resistance Welders."

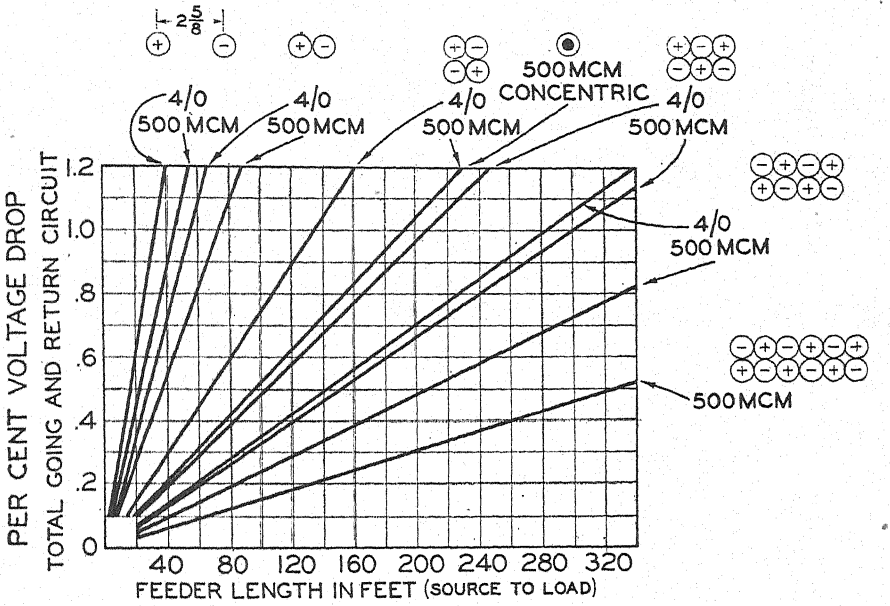


Fig. 9—Welding Supply—Wire Feeder Regulation (Per Cent Voltage Drop per 1000 Amp. of 30% Power Factor, Single-Phase Welding Current)

1. For 480-v. feeder, use chart values of per cent voltage drop.
2. For 240-v. feeder, multiply per cent voltage drop by 2.

E. MECHANICAL CHARACTERISTICS OF RESISTANCE WELDERS

Spot-Welding Machines

In making a spot weld, the equipment or machine used must apply the correct heat, localize it at the point where fusion (weld) is desired and apply the proper forging pressure at the proper instant. It is evident, therefore, that the factors governing the size and type of spot-welding machines can be divided into three groups: first, the factors which produce heat, second, the factors which localize the heat and, third, the factors which influence the forging pressure and its synchronization in the welding operation.

Upon selection of the values for the above factors, depend the size, type and capacity of the spot welder. These values can be determined from previous work or from data given in Chapters 9 and 10.

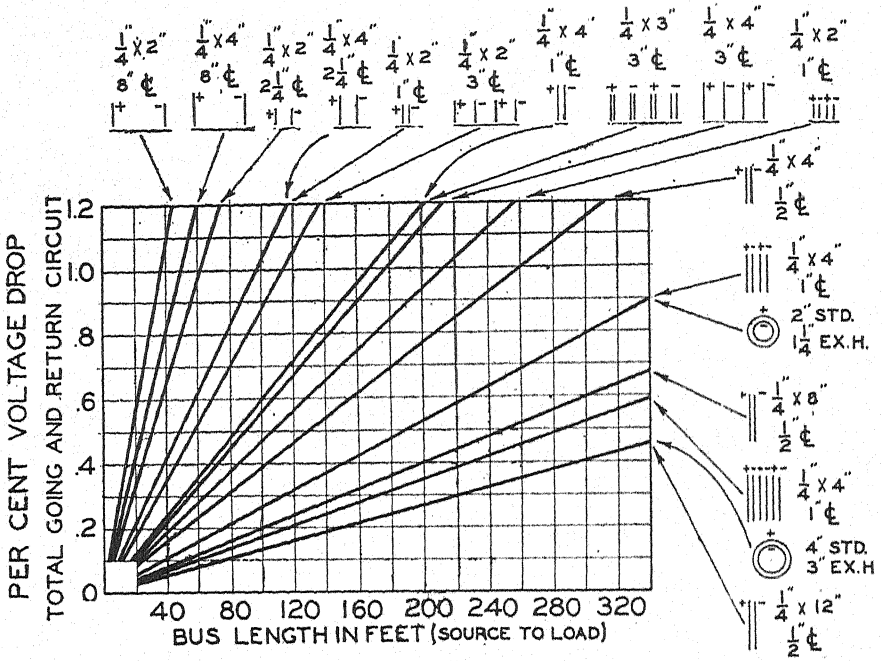


Fig. 10—Welding Supply—Bus Regulation (Per Cent Voltage Drop per 1000 Amp. of 30% Power Factor, Single-Phase Welding Current)

1. For 480-v. feeder, use chart values of per cent voltage drop.
2. For 240-v. feeder, multiply per cent voltage drop by 2.

Types of Spot Welders

The mechanical operation of standard spot welders for general job and production work will be covered in the following pages. It will be impossible to cover the many special spot welders in operation and since they too are governed by the above three factors, they are special only in physical contour and work-handling provisions, and are usually high production, single purpose machines.

The different types of spot-welding machines, outside of size or capacity, but in general physical appearance are: Rocker Arm Spot Welders, Fig. 11; Press Type Spot Welders, Fig. 12; Portable Spot Welders, Fig. 13; and Multi-Electrode (Point) Spot Welders, Fig. 14. All of these types have various methods of operation and cover a wide range in size and capacity.

Figure 15 shows a general division of the various types of spot welders with their standard method of operation. Figures in parentheses designate approximately the usual capacity for a single spot weld on clean, mild steel.

Further divisions will come solely through size or capacity, as shown by Tables 6 and 7 which give the pressure range as the maximum limit for the throat depth indicated, minimum values for long throat and maximum values for short throat depths. The maximum pressure values apply to air or hydraulically operated machines only.

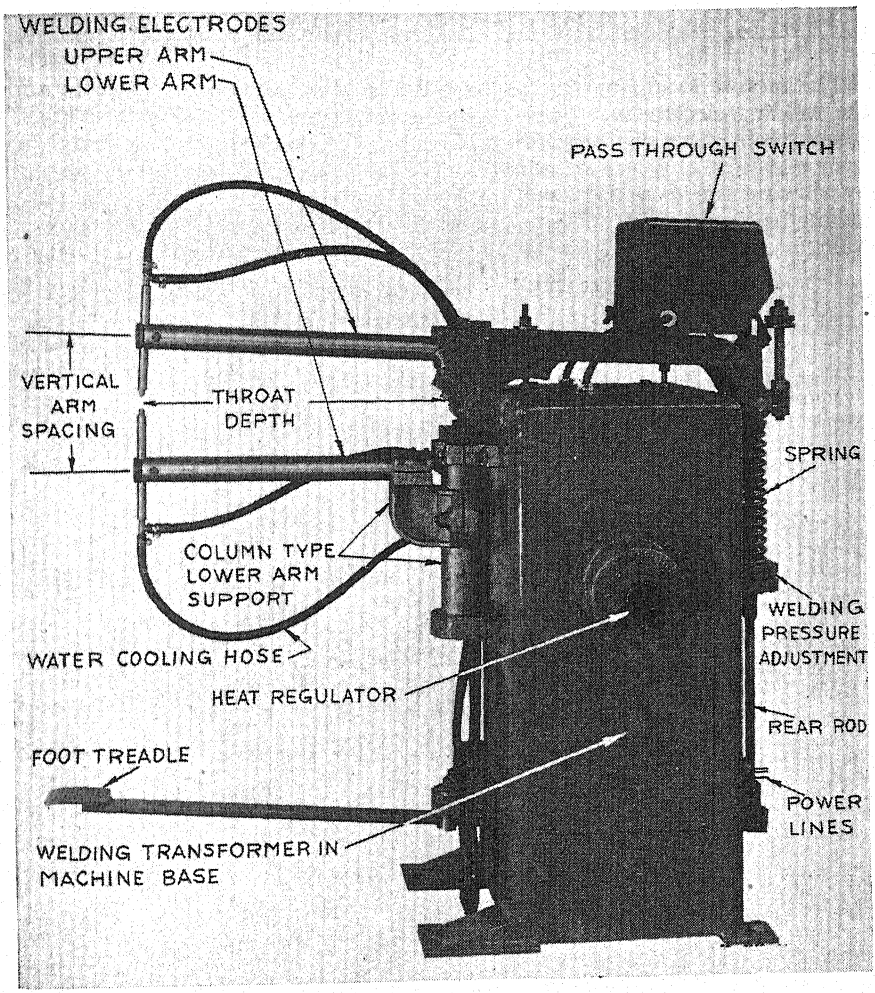


Fig. 11—Conventional Foot Operated Rocker Arm Type Spot Welder

The divisions of multi-electrode spot welders and portable welders will be referred to later in this chapter.

Mechanical Elements of Spot Welders

The factor that produces the heat for spot welding is, of course, the welding transformer (see Fig. 1). The kva. ratings in Tables 6 and 7 are nominal ratings, based on R.W.M.A. standards.

Table 6—Standard Sizes of Rocker Arm Type Spot Welders (R.W.M.A.)

Size	Transformer, Kva.	Standard Throat Depth, In.	Standard Pressure Range, Lb.
Small	10–15–20	6–12–18–24–30	170–500
Medium	20–30	12–18–24–30–36	280–1000
Large	40–50	12–18–24–30–36–42	315–1000

The factors localizing the heat are the welding arms or conductors and the welding electrodes. These elements are connected as shown in Fig. 1 where the primary winding with taps runs to the heat regulator. This regulator serves as a means for adjusting the magnitude of the welding current by varying the secondary voltage. The contactor switch—mechanically, magnetically or electronically operated—applies and cuts off the power. A flexible connection is provided to allow a motion between the contacting

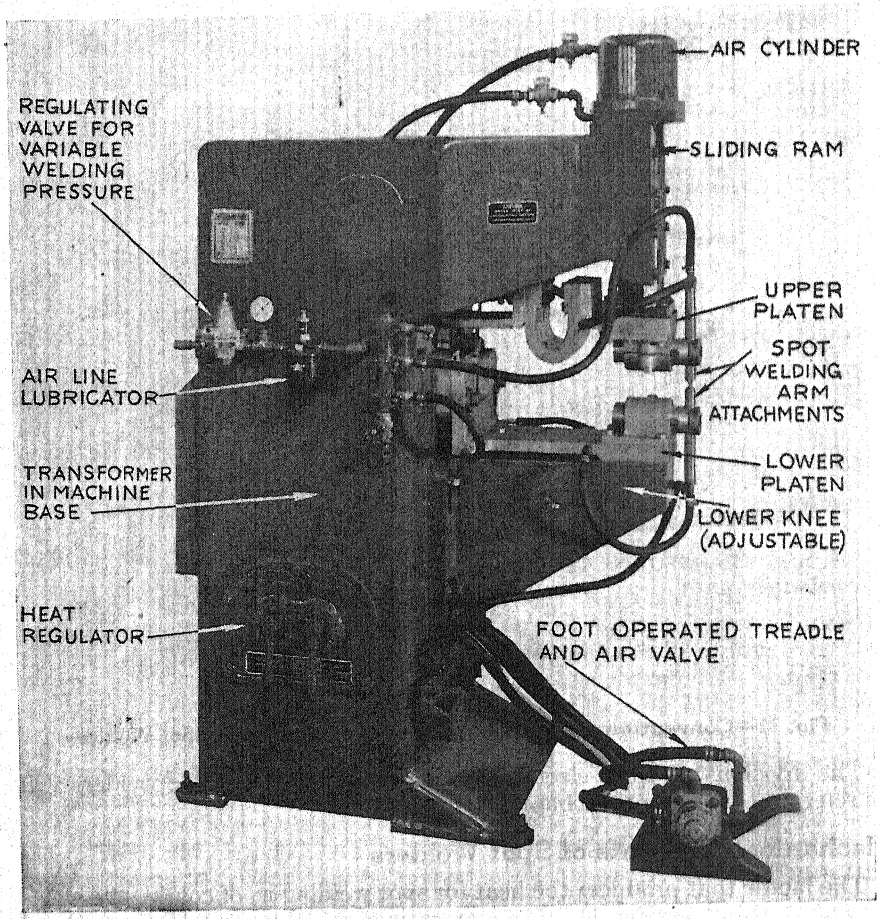


Fig. 12—Press Type Spot Welder (Air Operated)

Table 7—Standard Sizes of Press Type Spot or Projection Welders (R.W.M.A.)

Size	Transformer, Kva.	Standard Throat Depth, In.	Standard Pressure Range, Lb.
Light	30–40–50–75	12–18–24–30	1000–1575
Medium	75–100–125	12–18–24–30	2500–4000
Heavy	150–200–250	12–18–24–30	5000–9000
Extra heavy	250–300–400–500–600	12–18	12,000–18,000

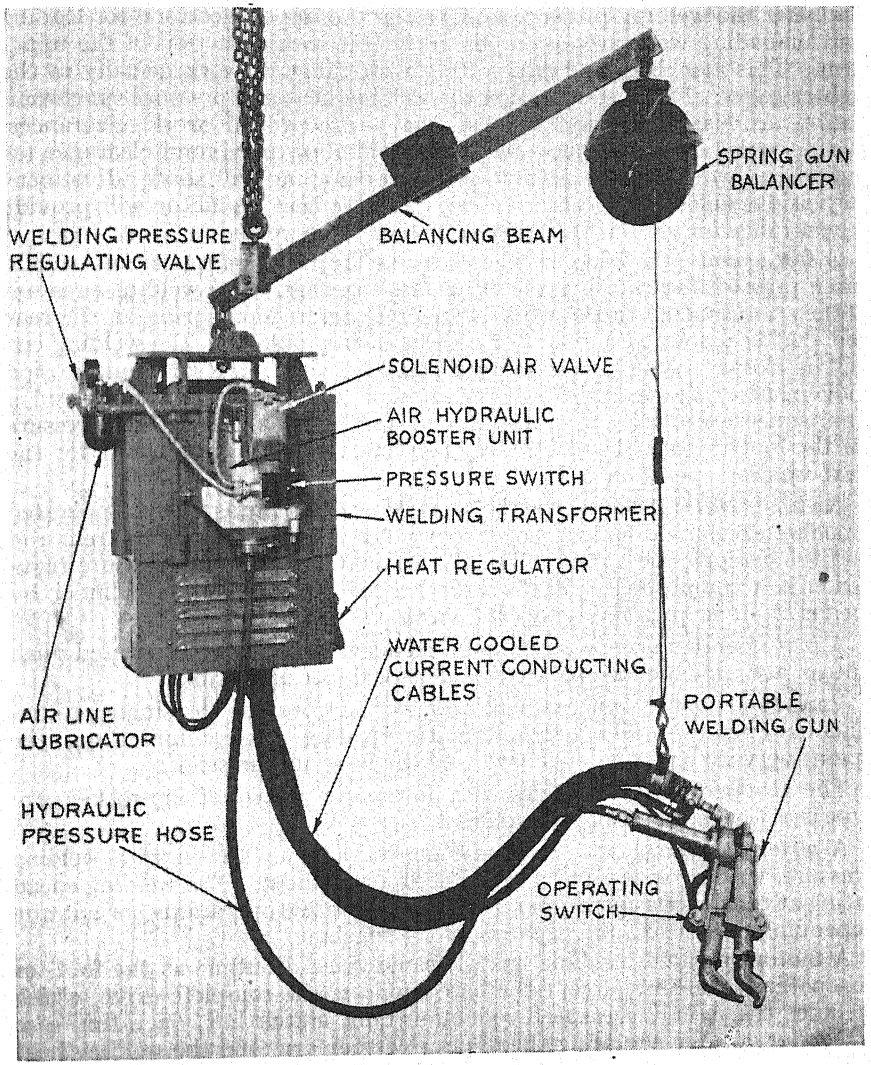


Fig. 13—Portable Type Spot Welder

electrodes. The current-carrying circuit connects the transformer secondary to the electrodes.

The factor influencing the forging pressure can be either manual (foot or hand operated), air, hydraulically operated or motor driven, which designation usually denotes the style of spot welder.

Synchronization of this forging pressure with the over-all welding cycle is accomplished through a mechanical pass-through switch for foot-operated machines; sequence electrical control for air or hydraulically operated machines; and a rotating cam control for motor-driven machines.

The *rocker arm spot welder* (Fig. 11) is so called because the means for applying the welding pressure and raising the upper electrode for loading and unloading work are accomplished by the rocking action of the upper arm. This machine is adaptable to a wide range of work, usually in the lighter gages. For foot operation the welding heat and pressure synchronization are variable, and the arms have exceptional work clearances. Water-cooled arms and short electrodes will allow maximum clearance for cylindrical work. The electrode and arm clamping will allow adjustment for various angles of electrode settings and the heat regulator will provide a heat range for various thicknesses of stock to be welded.

A *foot-operated* machine has a foot treadle (adjustable for position) which, when pressed down, brings the electrodes together. The welding pressure is then transmitted to the work through a compression spring on the rear rod. After a suitable amount of compression is obtained, the welding circuit is closed by means of the mechanical switch. As the compression movement of the rear rod follows through, the switch trip opens and a final squeeze pressure is applied to the weld. By releasing the pressure on the foot treadle, the electrodes open and the trip switch resets for the next welding operation.

An *air-operated* machine has the same general outline as the foot-operated machine except a double-acting air cylinder is connected to the rear rod and the compression spring is usually eliminated. Welding pressure regulation is accomplished through regulated air pressure to the cylinder by means of an air pressure regulating valve.

A foot-operated or a solenoid-operated air valve with foot-operated push button actuates the air-operated welder for upper arm stroke.

Various sequence controls (see Chapter 11) provide for single or continuous operation and full automatic welding cycle, eliminating the operating variables, and synchronizing the heat and pressure.

The air-operated spot welder with automatic control of the rocker arm type is a very desirable production tool.

A *motor-operated* machine is fully automatic in operation with welding pressure, welding speed and welding heat adjustment. The welding speed rating at continuous operation ranges from 30 to 200 operations per minute, depending on the size and capacity of the machine.

A motor-operated machine has the same general outline as the foot- or air-operated machine, except the base supports the complete drive, which includes the motor, the speed reduction unit, clutch box, operating cam and roller arm for actuating the upper electrode arm and the welding heat control cam. For actuation, a foot treadle is used for tripping the clutch for continuous or single spot operation as desired.

The adjustable fan type cam for welding heat control, mounted directly on the clutch box shaft extension, operates a roller type limit switch, which in turn actuates the magnetic contactor or whatever electronic control is being used. Full adjustment for closing and breaking the welding circuit and for setting the correct length of welding current dwell is provided, and full automatic operation is obtained with correct and adjustable synchronization of the forging pressure and the welding heat.

A press type spot or projection welder is illustrated in Fig. 12 and is available in sizes for welding the medium up to the heaviest of gages that can be spot or projection welded, and is so called because of the straight line (press action), vertical stroke of the upper welding head, so essential for projection welding.

The air-operated press welder shown in Fig. 12 has a direct-connected double-acting air cylinder adjustably tied to the ram which is guided by adjustable gibs and carries the upper platen (usually insulated) on a slide face as shown. This assembly provides for welding stroke and welding pressure application. The lower knee and the machine in general are designed for a minimum of deflection under the heavier range of pressures required for spot and projection welding.

The air cylinder can be of various designs to suit different types of ram operation and stroke adjustment.

The motor-driven press welder, like the rocker arm spot welder, has a motor, variable speed drive and clutch box with same type of adjustable fan cam synchronizing the heat and pressure. However, various arrangements to obtain the necessary stroke for the ram are employed.

The speed of operation depends on the size of the machine and the type of work to be welded. The over-all speed range of motor-driven press type welders ranges from 10 to 200 operations per minute, figuring, of course, on continuous running.

A hydraulically operated press type spot and projection welder is usually of the heavier sizes and capacity, but still follows the general design of the air-operated equipment. However, these machines are self-contained, with motor, hydraulic pump, and relief and control valves for ram actuation and pressure application.

The 4-way control valve can be either solenoid or pilot circuit operated. The pressure switch synchronizes the welding pressure with the heat control and the relief valve adjustment provides for the amount of welding pressure desired and maintains some pressure in the bottom of the cylinder to hold the ram up at all times.

Variations of the hydraulic hook-up circuit follow different types of pump installations and methods of operation for special requirements.

Accessories for Spot- or Projection-Welding Machines

There can be added to standard machines various auxiliary provisions for increasing the range of adaptability for various work, and for refinements in operation.

On rocker arm spot welders these consist of special control apparatus, "Universal Type" electrode holding arms, having electrode mounting at 90° or vertical at one end and 30° from vertical, or angle mounting, on the

opposite end. In place of the compression spring, a finer degree of pressure regulation can be obtained through air cylinder and static regulated pressure, commonly called "air-lock" or "air-cushion," and various means are used for supporting the lower arm to obtain a wide range of "vertical arm spacing" adjustment and flexibility.

For air-operated and motor-driven machines, a solenoid-operated valve or a solenoid-operated clutch control, respectively, using a push button foot-operated control, may be employed.

For press welders the same auxiliaries as above can be added and, in addition, a low inertia (weight) type of ram and welding head and an "air reservoir tank" for a fine degree of welding pressure application can be specified.

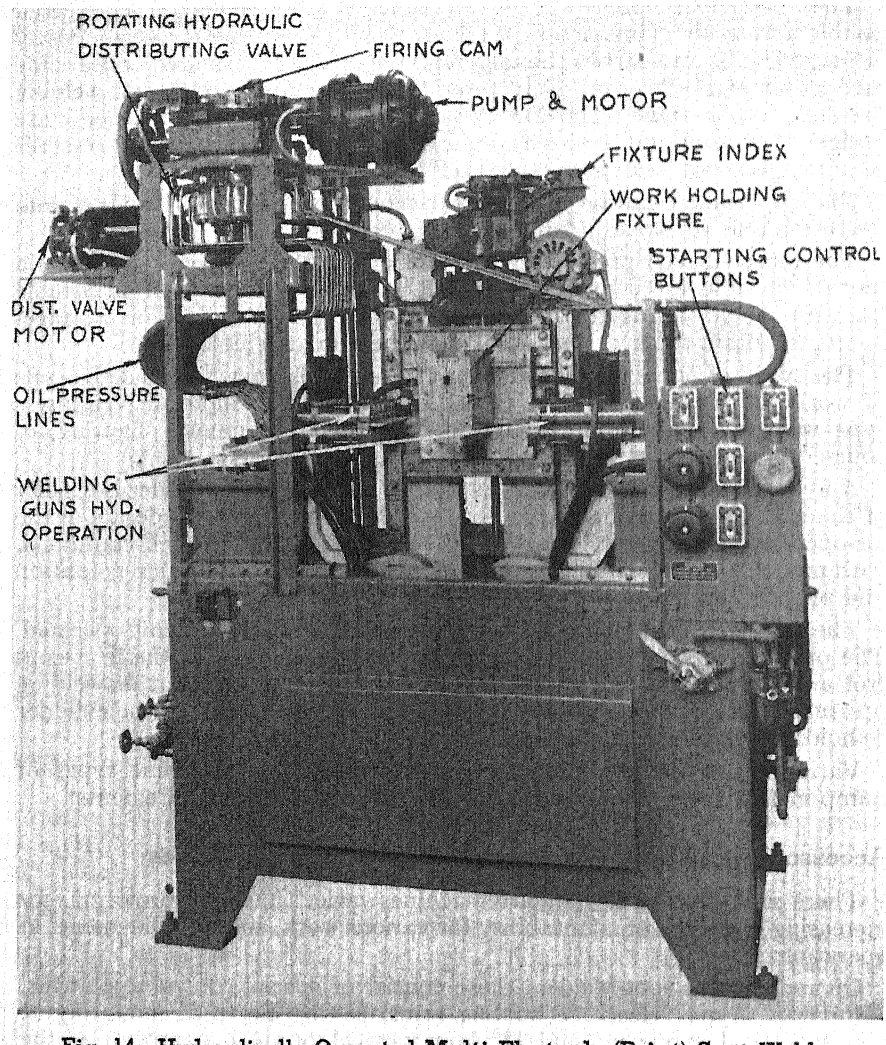


Fig. 14—Hydraulically Operated Multi-Electrode (Point) Spot Welder

Portable and Multi-Electrode Spot Welders

Portable and multi-electrode spot welders illustrated in Figs. 13 and 14, respectively, show the elements usually constituting these types of equipment. Both of these types of machines are especially designed to suit the job and the fundamental characteristics are fully described in Chapters 9 and 10.

A portable spot welder, as the name implies, is a welding tool rather than a welding machine. Its welding capacity is determined by the transformer capacity, length of water-cooled current-conducting cable and the size and shape of the portable gun used.

The multi-electrode spot welder is usually fully automatic in operation and control and a multiplicity of electrodes (points) and transformers is used. This type of spot-welding equipment is usually a single-purpose, specially constructed machine, and may have from two to as many as 100 or more spot-welding electrodes arranged in the proper positions to make the required number of welds.

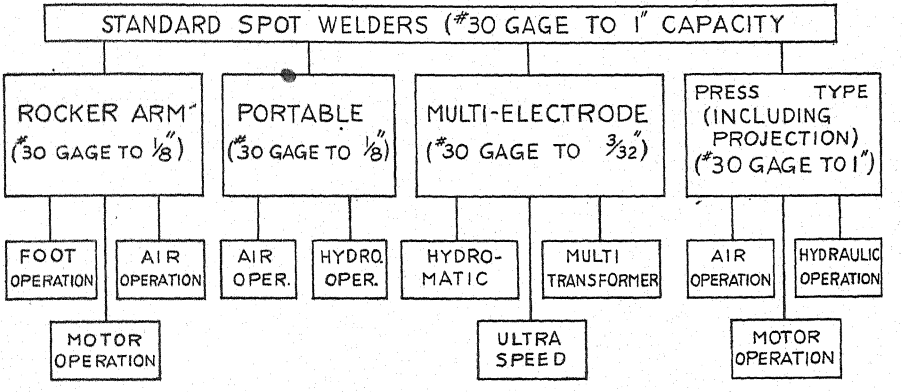


Fig. 15—General Division of Spot Welder Types

Figure 14 illustrates such an equipment and a machine usually consists of a fabricated frame of the size and shape necessary to accommodate the particular structure to be spot welded and the sub-members to mount the welding electrodes in the proper position to make the required number of welds. Work holding fixtures and clamps to hold the work in position while welding are often essential.

The welding guns are usually hydraulically operated with welding points mounted directly under the cylinder assemblies. These electrode assemblies are controlled by rotary or lineal travel valves which operate one or more welding stations in sequence. Attached to the valve mechanism is a cam used to control the timing device through the proper switches or electronic control.

Seam-Welding Machines

The same general characteristics as given for spot-welding machines are applicable to seam-welding machines.

Types of Seam Welders

The different types of standard seam-welding machines outside of size or capacity are: single-purpose longitudinal seam welders; single-purpose circular seam welders; or combination longitudinal and circular seam welders (Universal type, for both straight and circular seam welding).

The longitudinal seam welder is for the welding of such work as is fed into the machine throat depth, and consists, mainly, of cylindrical work—welding the side or straight seams thereof.

The circular seam welder, as the name implies, welds the circular or end seams of the cylindrical piece of work with the work either projecting into the machine throat depth, or projecting away from the welding wheels toward the operator, as required. For exceptionally long lengths of flat seams, the circular seam welder is also used, permitting comparatively short machine throat depth (for increased over-all electrical efficiency) and still allowing it to produce, if necessary, an indefinite length of seam.

The combination longitudinal and circular machine or universal type, as it is commonly known, is one which permits the upper welding head to be swiveled 90° to allow for both of the above set-ups. With the Universal type machine it naturally follows that lower arms with both types of welding wheel facilities must be supplied, that is, one longitudinal seam arm and one circular seam arm. In the machine illustrated in Fig. 16, for a combination seam welder, both of the lower arms are mounted on the machine, hinged in such a manner that either can be swung into position as desired.

The size and transformer capacity of standard seam welders are given in Table 8. The pressure range is the total maximum and minimum pressure adjustments for each size machine. The capacity and stock to be welded are governed by so many variables that further study of fundamentals in Chapter 9 is necessary to determine the capacities for the sizes of the seam welders given.

Table 8—Standard Sizes of Seam Welders (R.W.M.A.)

Size	Transformer, Kva.	Standard Throat Depths, In.	Standard Pressure Range, Lb.
Light	50–75	18–24–30–36	200–1200
Medium	125–150–200	18–24–30–36–42–48	300–2400
Heavy	250–300–400	24–30–36–42–48	350–3200

Mechanical Elements of Seam Welders

The factors that produce the heat and localize same for seam welding are identical to those required for spot welding (see Fig. 1), except welding wheels are used instead of spot-welding electrodes.

The factor influencing the forging pressure is usually a directly connected air cylinder under regulated air pressure. However, static weight, spring or hydraulic pressure are sometimes used for special requirements.

Synchronization of this forging pressure with the over-all welding cycle is accomplished through a mechanical limit switch combined with the foot

operating treadle or a solenoid air valve and push button and an automatic air line pressure switch, which is closed when the welding wheels are on the work under the desired welding pressure. This sequence must be automatic to insure the welding heat circuit being closed only when the wheels are on the work under pressure at the beginning and the end of the seam to be welded.

Referring to Fig. 16, the machine base houses the welding transformer and a portion of the machine drive. The upper arm supports the ram.

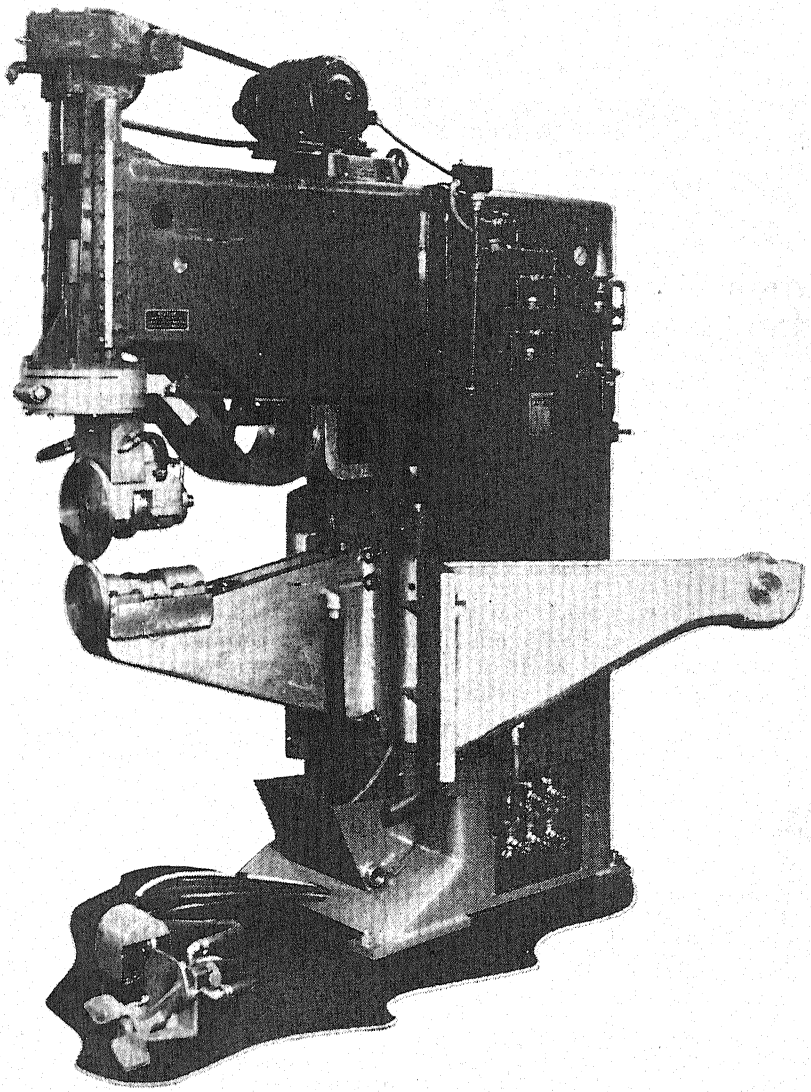


Fig. 16—Universal Seam Welder with Hinge Mounted Lower Arms

welding head and operating cylinder for ram stroke and welding pressure application. The lower arm supports the lower welding wheel assembly and an efficient water-cooling system completes these elements.

The machine drive consists of a motor and variable speed drive, through a reduction unit and shafts extending to the welding wheels. This shaft extension utilizes two universal joints to allow for welding head vertical stroke, when the upper welding wheel is the driving member.

Mechanical adjustments are provided for: (*a*) welding wheel wear, bringing the upper head down or the lower up (the illustration referred to shows the adjusting nuts at the ram and cylinder connection for this purpose); (*b*) welding speed adjustment through the variable speed drive covering a standard range of 3 to 1 with over-all welding speeds available between 1 and 30 ft. per minute depending on the work to be seam welded; (*c*) welding heat adjustments through the heat regulator, or other means within the control; and (*d*) welding pressure adjustments through a regulating air pressure valve, static weights or compression spring.

For welding current adjustment and description for seam-welding control see Chapter 11.

Types of Welding Wheel Drives for Standard Seam Welders

There are several types of standard welding wheel driving mechanisms available and each has certain advantages. A brief description of these types of standard drives follows.

Upper Wheel Gear Drive.—As the name implies, a machine so equipped has only the upper wheel driven by means of gears. The lower wheel is an idler. The drive is from the motor through variable speed motor pulley to an enclosed worm reduction through universal joints to gear-driven upper wheel.

This type of drive is recommended when lower arm clearances are limited.

Lower Wheel Gear Drive.—As the name implies, a machine so equipped has only the lower welding wheel driven by means of gears. The upper wheel is an idler. The drive is from the motor through a variable motor pulley to an enclosed worm reduction through spur gears (and universal joints) to gear-driven lower wheel.

This type of drive is usually recommended only for circular seam welding when the diameter of the lower wheel must be very small, inasmuch as small diameter wheels turn better when driven. This type of drive may be either a gear drive located just back of the wheel (for bottoms of containers or other circular seams), or a gear drive located back of the wheel shaft bearing (to permit small diameter cylinders to fit over the arm for welding in heads of containers or other similar work).

NOTE: Both of the above types are classified as single wheel gear-driven machines and they are standardly available as single-purpose machines for either longitudinal or circular seams (not both), with a fixed upper welding head.

Upper Wheel Knurl Drive.—As the name implies, a machine so equipped has the upper wheel driven at its periphery by a hardened steel roller. This driving roller may have its face smooth or knurled, depending upon the work to be welded. The drive is from the motor through variable speed

motor pulley to an enclosed worm reduction, driving the shaft extension which, in turn, through flexible universal joints drives the so-called steel knurl or driving roller through its assembly mounted on the upper welding head. The knurl assembly is provided with adjustable driving roll pressure. The driving roller acts as a forming roll and maintains a constant uniform welding face on the upper welding wheel.

Lower Wheel Knurl Drive.—As the name implies, a machine so equipped has the lower wheel driven at its periphery by a hardened steel roller. This driving roller may have its face smooth or knurled, depending upon the work to be welded. The drive is from the motor through a variable speed motor pulley to an enclosed worm reduction, driving the shaft extension which, in turn, through flexible universal joints drives the so-called steel knurl or driving roller through its assembly mounted on the lower welding head. The knurl assembly is provided with adjustable driving roll pressure. The driving roller acts as a forming roll and maintains a constant uniform welding face on the lower welding wheel.

Double Wheel Knurl Drive.—As the name implies, a machine so equipped has both the upper and lower wheels driven at their peripheries by hardened steel rollers. These driving rollers may have their faces smooth or knurled, depending upon the work to be welded. The drive is from the motor through a variable speed motor pulley to an enclosed worm reduction, driving the two shaft extensions which in turn, through flexible universal joints, drive the so-called steel knurls or driving rollers through their respective assemblies mounted on each welding head. The driving rollers act as forming rolls and maintain a constant uniform welding face on the welding wheels, and regardless of welding wheel wear or diameter a constant linear welding speed is maintained at all times.

NOTE: The above type is classified as a double wheel knurl-driven machine and is standardly available as a single-purpose machine for either longitudinal or circular seams, with a fixed upper welding head.

Upper Wheel Gear Drive Universal (Combination Longitudinal and Circular Seam Welder).—As the name implies, a machine so equipped has only the upper wheel driven by means of gears. The drive is from the motor through a variable speed motor pulley to an enclosed worm reduction through spur gears and universal joints to the gear-driven upper wheel. The upper head is so designed that it can be rotated 90° and can weld either straight or circular seams. This machine further utilizes two lower arms, one for longitudinal seams and one for circular seams, with idler welding wheels.

Upper Wheel Knurl Drive Universal (Combination Longitudinal and Circular Seam Welder).—As the name implies, a machine so equipped has only the upper wheel driven at its periphery by a hardened steel roller. This driving roller may have a smooth face or a knurled face, depending upon its particular work. For drive, the regular enclosed drive unit is employed which is connected to the upper head only. The upper head is so designed that it can be rotated 90° and can weld either longitudinal or circular seams. It further utilizes two lower arms, one of each type (longitudinal and circular), with idler welding wheels.

Double Wheel Knurl Drive Universal (Combination Longitudinal and Circular Seam Welder).—As the name implies, a machine so equipped will have

both upper and lower wheels driven at their peripheries by hardened steel rollers, all in accordance with the above double wheel knurl drive description, the exception being that the drive is so arranged that the upper welding head can be swiveled 90° to permit the welding of both longitudinal and circular seams.

Semi-Standard Seam Welders.—A further division of seam-welding machines will include those of a semi-standard nature such as: (*a*) a traveling wheel, where the work is clamped and held stationary while a roll and welding head carriage travel over the work to complete the seam; (*b*) a traveling platen type seam welder, where the welding wheel and head are stationary and the work clamped and jigged on a moving slide or platen, traveling under or over the roll to complete the seam; and (*c*) multi-wheel seam welders, which through the Series Weld principle, or Multiple-Welding transformers, provide for the welding of more than one seam simultaneously.

Flash and Butt Welders

The same general requirements apply for flash- and butt-welding machines as are given for spot-welding machines.

Types of Flash and Butt Welders

The main divisions of standard flash and butt welders outside of size or capacity are: whether the equipment is a flash welder or a butt welder; and the means employed for actuating the push-up or forging pressure.

Table 9—Various Classes of Butt and Flash Welders—Their Uses and Mechanisms

Class	Type of Push-up	Flash Welding Only	Butt Welding Only	Flash or Butt Welding	Used for	Mechanism
1	Hand	X	X	X	General purpose or low production on ferrous metals	(*A*) Direct leverage (*B*) Leverage through toggle (*C*) Leverage through hydraulic jack
2	Spring	...	X	...	Non-ferrous metals, hand or automatic welding control	Direct spring pressure with hand or automatic return
3	Weight	...	X	...	Same as Class 2	Direct leverage with adjustable weight position with hand or automatic return
4	Air cylinder	...	X	...	High-production ferrous metals	Direct-connected double-acting air cylinder and automatic sequence control
5	Motor	X	...	...	General purpose high-production (medium duty)	Cam operated through speed reduction with single or variable speed drive
6	Hydraulic operation	X	X	X	General purpose low- and high-production (heavy duty) ferrous metals	(*A*) High pressure from shop accumulator system (*B*) Self-contained hydraulic pump and motor unit, with automatic or hand valve control

Table 10—Standard (R.W.M.A.) and Special Sizes of Flash and Butt Welders

Size Machine	Transformer Kva.	Max. Upset Pressure, Lb.	Welding Capacity (Steel) Projected Area (Sq. In.) × Max. Width (In.)					
			Class 1, A and B	Class 1C	Classes 2 and 3	Class 4	Class 5	Class 6
1	5	500	0.15 sq. in. × 2 in.	...	0.03 sq. in.	0.03 sq. in.	...	...
2	10	1,500	0.30 sq. in. × 2 in.	...	0.11 sq. in. × 2 in.	0.11 sq. in. × 2 in.	0.10 sq. in. × 2 in.	...
2	20	1,500	0.45 sq. in. × 2 in.	...	0.15 sq. in. × 2 in.	0.15 sq. in. × 2 in	0.15 sq. in. × 2 in	...
3	30	3,000	0.60 sq. in. × 4 in.	...	...	0.20 sq. in. × 4 in.	0.20 sq. in. × 4 in.	...
3	50	3,000	0.90 sq. in. × 4 in.	...	...	0.25 sq. in. × 4 in.	0.30 sq. in. × 4 in.	...
4	75	5,000	1.2 sq. in. × 6 in.	...	...	0.44 sq. in. × 6 in.	0.40 sq. in. × 6 in.	...
4	100	5,000	1.5 sq. in. × 6 in.	...	...	0.50 sq. in. × 6 in.	0.50 sq. in. × 6 in.	...
5	100	12,000	1.8 sq. in. × 8 in.	...	...	0.60 sq. in. × 8 in.	0.60 sq. in. × 8 in.	...
5	125	12,000	2.4 sq. in. × 8 in.	...	...	0.80 sq. in. × 8 in.	0.80 sq. in. × 8 in.	...
5	150	12,000	3.0 sq. in. × 8 in.	...	...	1.2 sq. in. × 8 in.	1.0 sq. in. × 8 in.	...
					Semi-Special Equipment			
6	200	25,000	...	4 sq. in.	...	...	2 sq. in.	...
6	250	25,000	...	5 sq. in.	...	...	$2^1/_2$ sq. in.	...
6	300	25,000	...	6 sq. in.	...	...	$2^3/_4$ sq. in.	...
7	300	60,000	...	6 sq. in.	...	...	...	3 sq. in.
7	400	60,000	...	8 sq. in.	...	...	...	4 sq. in.
7	500	60,000	...	10 sq. in.	...	...	...	5 sq. in.

Standard divisions, outside of size or capacity, are in the types of clamping used for the work.

The fundamental difference between flash and butt welding is given in Chapter 9, and only the mechanical fundamentals of the equipment will be treated in this section.

Table 9 lists the various standard classes of machine operation, the type of push-up being the classification of the respective groups of equipment.

Table 10 shows the usual standard divisions of size and capacity for each of the above classifications with welding capacities given in the projected area to be welded. For relative capacities for other materials and shapes see Chapter 9.

As in other types of resistance welding, there are machines of lesser and greater capacity and size than those given. These, however, will incorporate the same general mechanical fundamentals as will be covered in the further description of the machines as listed.

Mechanical Characteristics of Flash and Butt Welders

The factors that produce the heat and localize same for flash and butt welding are identical to those required for spot welding (see Fig. 1), except that work clamp assemblies are used instead of spot-welding electrodes, the fundamental difference being that, in spot or seam welding, the electrodes contact the work at a point of fusion, whereas in flash and butt welding the work is clamped at a place adjacent to the point of fusion and the forging pressure is transmitted to the work through clamp assemblies.

The factor influencing the forging pressure and synchronizing same with the over-all welding cycle is most varied in flash or butt welding equipment and therefore the machines have a wide division of operation as shown by Tables 9 and 10.

Shown in Fig. 17 is the hand-operated flash or butt welder. The stationary and moving platens supporting the clamp assemblies are connected to the welding transformer in the machine base, and the hand lever provides the actuation for the moving platen. Synchronism of welding heat and pressure by the push button on hand lever is through a magnetic welding contactor and, for flash welding, an automatic cut-out switch for breaking circuit (operated from moving platen) is provided.

A spring-operated push-up is used where a quick and automatic forging pressure is required and is used on small sections, particularly copper rod or wire welding so when the hand lever opens the moving platen against the spring, a lock holds same while work is loaded and clamped. The spring is then released and through a tripped cut-out switch the automatic synchronization of heat and forging pressure is obtained.

Weights, through leverage, or mounted directly on a cable and pulley, are sometimes used in place of springs for push-up, with the same resulting operation.

The motor-operated flash welder has the same basic elements as a hand-operated flash welder except the moving platen actuation is through a motor, a variable speed drive to a gear reduction and operating cam with an adjustable roller, mounted on the moving platen.

The operating cam incorporates the various distinct divisions in its contour, and through a motor control operates through one revolution for each operating cycle, started by push button. Figure 18 illustrates the flash-welding cam contour for general application.

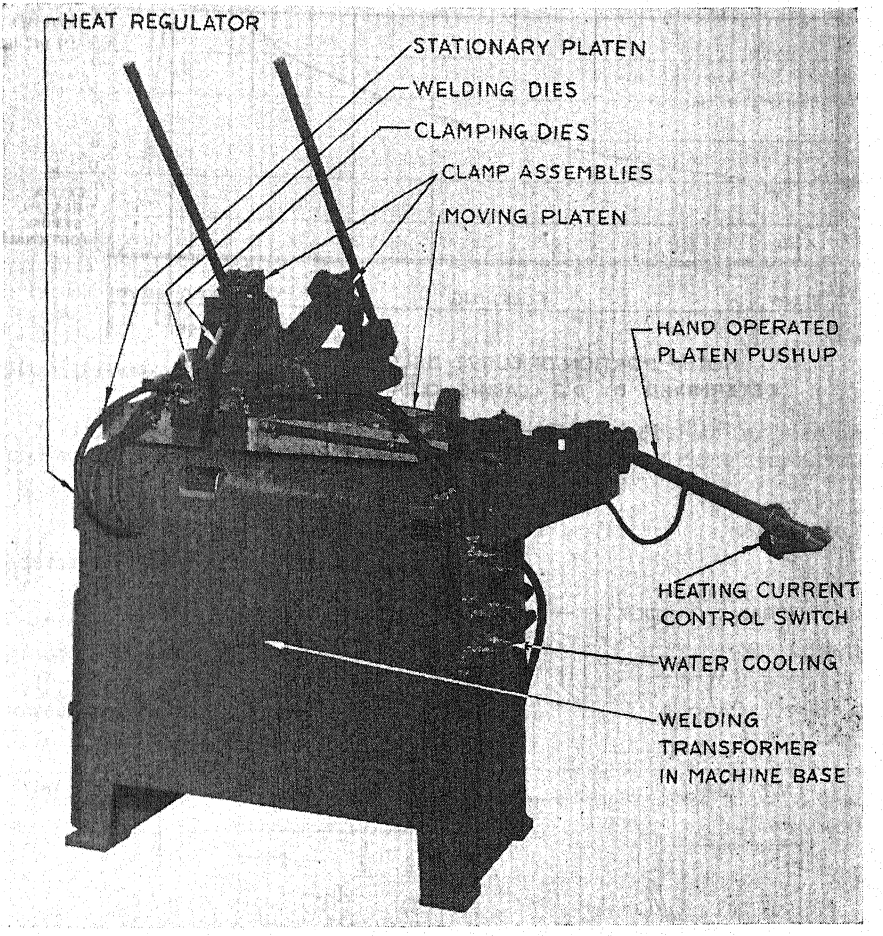


Fig. 17—Hand Toggle Push-up (or Upset) Butt or Flash Welder with Hand Operated Clamps

The motor-driven machine is fully automatic in operation through the auxiliary sequence control cams mounted on the operating cam shaft, providing the synchronization of heat and forging pressure and motor control for each operating cycle. While speed and control adjustments are provided, the motor-operated machine necessarily does not handle the

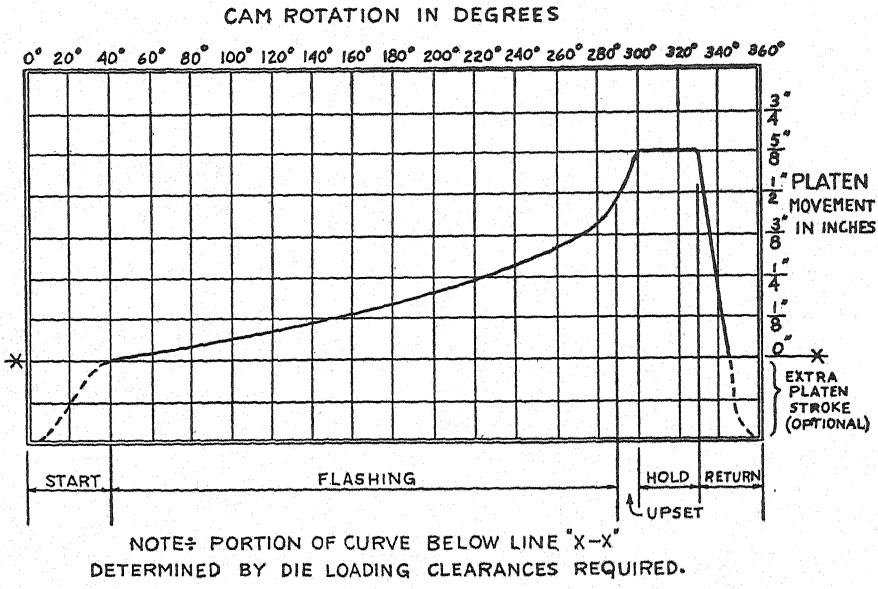


Fig. 18—Typical Flash Welder Cam Curve

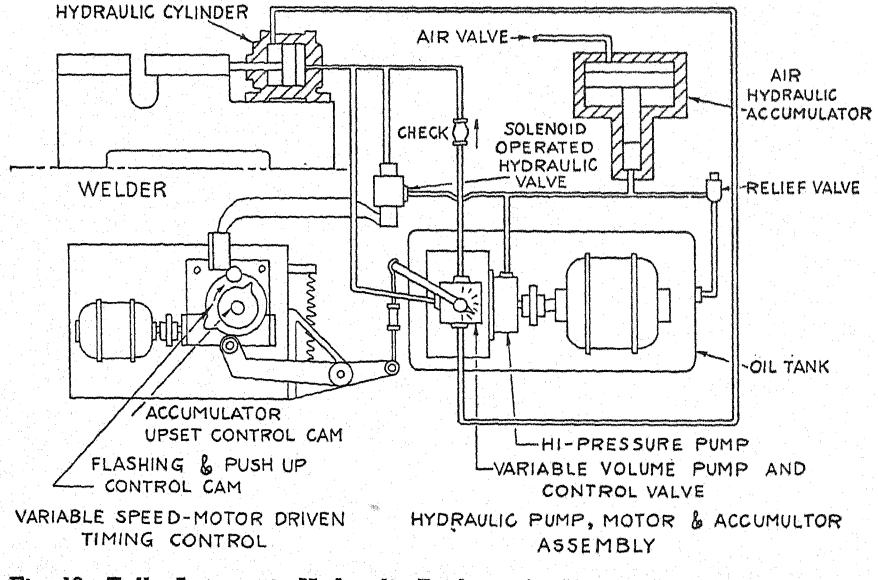


Fig. 19—Fully Automatic Hydraulic Push-up (or Upset) Flash Welder Piping Diagram

wide range of work that can be welded on a hand-operated machine. However, its operation will be more consistent and this type is the most widely used today for high production work.

Hydraulically operated butt or flash welders can be either the so-called "hand-jack" operated or the hydraulic cylinder-operated type, with the latter type including hydraulic pressure from a shop accumulator system or self-contained hydraulic pump unit which is part of the welder.

The hydraulic cylinder-operated machines can be either hand controlled through a variable speed lever or through an automatic control for speed of platen push-up during the flashing and upset, with automatic current control for forging pressure synchronization.

Figure 19 shows a full automatic, hydraulically operated circuit by a simplified diagram to better illustrate the principles of operation. Approximately 1000 psi. hydraulic line pressure is used and hydraulic operation, especially in the heavier sizes and capacities of flash and butt welders provides the high push-up pressure not readily obtainable in hand-operated or motor-driven equipment.

Clamp Assemblies for Butt and Flash Welders

Of equal importance to the method used for platen push-up in flash or butt welders is the type of clamp assemblies mounted on these machines. Fig. 20 shows the usual standard forms of clamp assemblies used.

Accessories for Flash and Butt Welders

In addition to standard operation of flash and butt welders, various arrangements can be made of a semi-standard nature to increase production or adaptability of the equipment.

To increase production, automatic clamp operation can be used with a motor-operated machine and air-operated clamps, through solenoid valve control and auxiliary switch operating cam on the operating cam shaft.

To follow quickly with the forging pressure on Classes Nos. 2 and 3 machines, Table 9, the moving platen can be of light construction and mounted on ball or roller bearings.

To allow for ease of loading and unloading, the platens can be arranged on an angle of 45° or 30° from the horizontal.

For the flash or butt welding of high carbon wire or strip, an annealing auxiliary control can be added to a standard machine which can be either manual or automatic in operation.

Summary

For resistance welding equipment, a greater degree of over-all range of size and operation of the machines is required than on any other type of machine tool used for high production and labor saving operation.

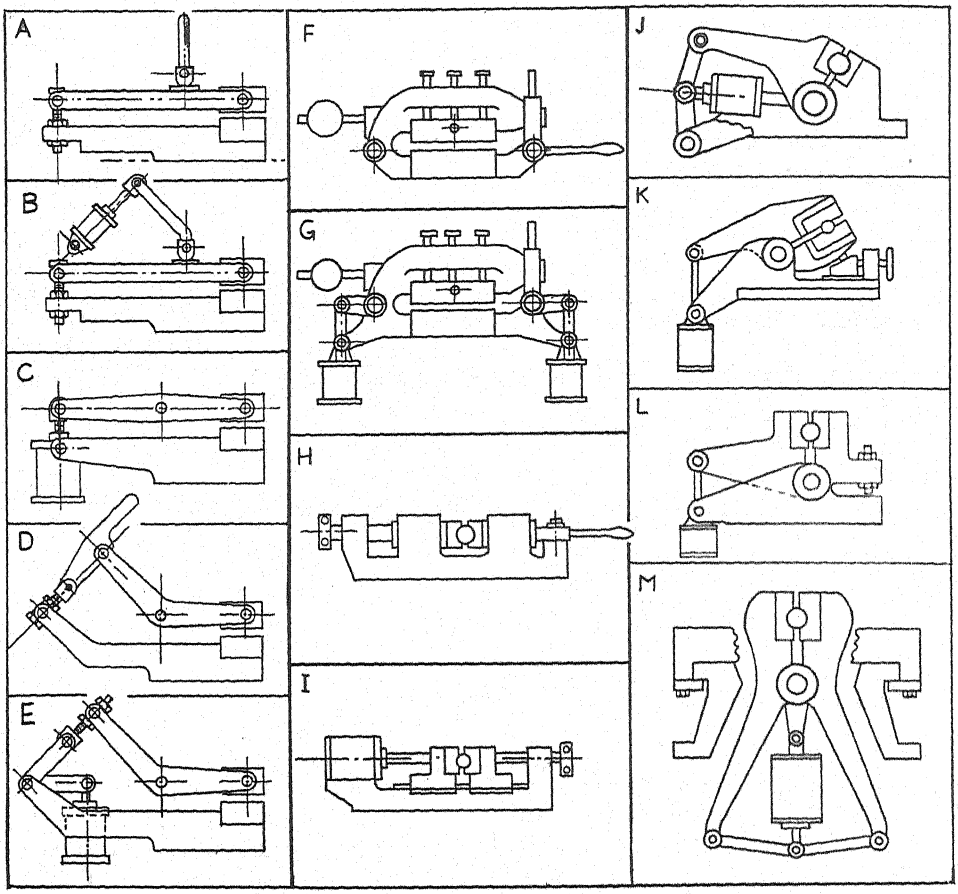


Fig. 20—Flash and Butt Welding Clamp Assemblies. Upper Jaws Steel, Lower Die Hard Copper

A—Vertical-Hand Operated (Cam) Open End Clamps.
B—Vertical-Air Operated (Cam) Open End Clamps.
C—Vertical-Direct Air Operated. Open End Clamps.
D—Vertical-Hand Operated. Open End Clamps.
E—Vertical-Air Operated (Toggle) Open End Clamps.
F—Vertical Open End Gate Type Hinged Clamps (Hand Operated).
G—Vertical Open End Gate Type Hinged Clamps (Air or Hydraulic Operated).
H—Horizontal Hand Operated Clamps.
I—Horizontal Air Operated Clamps.
J—Angle-Air Operated (Toggle) Open End Clamps Heavy Duty.
K—Angle-Air Operated (Direct) Open End Clamps Light Duty.
L—Horizontal Hinged Air Operated (Direct) Open End Clamps Light & Medium Duty.
M—Horizontal Hinged Air Operated (Toggle) Open End Clamps Heavy Duty.

In the foregoing chapter no attempt was made to cover in detail this range, nor the many special adaptations for single purpose machines or for special work, and for detail requirements further reference to Chapter 9, wherein the fundamental requirements of resistance welding is outlined, will show the possible range of work and type of welding equipment required—to suit the production desired.

CHAPTER 9

RESISTANCE WELDING PROCESSES*

Spot Welding, Projection Welding, Seam Welding, Flash and Upset Butt Welding, and Special Processes.

SPOT WELDING

General Principles of Spot Welding

SPOT welding, in its simplest application, consists merely of clamping two or more pieces of sheet metal between two copper or copper alloy welding tips and passing an electric current of sufficient strength through the pieces to cause welding or bonding of the pieces. Figure 1 shows this application.

Figure 2 shows the complete welding circuit. A current circulates through the transformer secondaries, flexible bands, horns or arms, electrodes and work as shown. Heat is generated in all portions of the circuit according to: H is proportional to I^2R in which I is the current, and R is the resistance. Assume the arms and electrodes to be of copper, 2 in. and 1 in. diameter, respectively, and the tip diameter D, Fig. 1, to be $^1/_4$ in., and 10,000 amp. flowing.

The current density in the arms will be 3180 amp. per sq. in., in the electrodes, 12,700 amp. per sq. in. and at the electrode tip and through the work, 200,000 amp. per sq. in. Applying these values to the above formula, if the heat generated per unit section in the arms is taken as 1, it will be 16 for the electrodes and approximately 4000 for the electrode tip. If the material being welded is steel, which has a resistance of approximately 8 times that of copper, then the unit heat generated in the work is approximately 32,000. The total heat generated is expressed by $H=I^2RT$, in which T is the length of time current is flowing. Therefore, neglecting heat losses due to conduction and radiation, the steel between the electrodes will be heated to a given temperature in $^1/_{32,000}$ of the time required for the arm to reach the same temperature, and $^1/_{2000}$ of the time for the electrode. However, there are other factors involved which must also be taken into

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consideration. All metals have scale or oxide films on their surface, the resistance of which is variable and very difficult to calculate, but is approximately inversely proportional to the contact pressure. Figure 3 shows a calculated instantaneous temperature chart. It will be noted that there are three zones of heat generation—the contact surface between the steel sheets, and the other two at the contacts of the sheet with the electrodes.

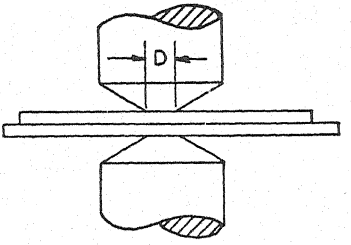


Fig. 1—Simple Application of Spot Welding

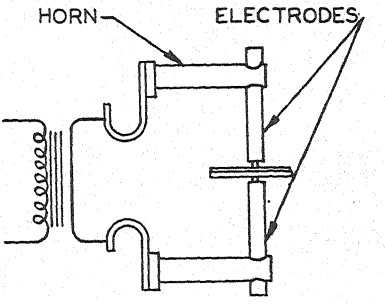


Fig. 2—Complete Spot-Welding Circuit

The heat conductivity of steel is approximately $^1/_{10}$ that of copper, so the heat generated along the surface *A*, Fig. 4, cannot radiate rapidly, whereas the heat generated at *B* can radiate rapidly into the electrodes. The result is, that the surface *A* is the first to reach a fusing temperature, and a weld takes place there. The heat zone as shown in Fig. 4 can be controlled by the proper application of time, current and pressure. As has already been shown, the total heat generated is a product of the time, current squared and the resistance, to which must be added a fourth factor, a variable representing heat conduction and radiation. Referring again to Fig. 4, the curved lines may be considered as successive heat waves at the instant current is applied. If the current is weak, heat generation will be slow and radiation relatively fast, so that by the time the center is hot enough to fuse together, the entire thickness of the metal will have become red hot and the electrodes will imbed themselves deeply into the metal and even the metal outside of the electrodes may become red hot and burned. If radiation and conduction could be eliminated, a weld could be accomplished with any current density if sufficient time were allowed. Since this is not possible, there is a low limit of current density below which a weld cannot be made, because the heat generated by the current is dissipated into the electrodes, surrounding air and that part of the metal outside of the electrodes, as fast as it can be generated. As the current density is increased, the time required is decreased. This increase in current may be carried to the point (in some instances) where a weld can be made without the surfaces *B* showing indication of having ever attained a temperature of over a few hundred degrees.

There is a very definite low limit for current values employed below which fusion cannot be obtained. For any selected welding pressure, there is also a very definite upper limit of current values beyond which explo-

sions (also known as "spitting," "squirting" or "expulsions") of hot metal take place at one or more surfaces of the material welded. Such explosions cause low quality welds, but maximum spot strength is obtained at a current density just short of the value at which expulsion takes place.

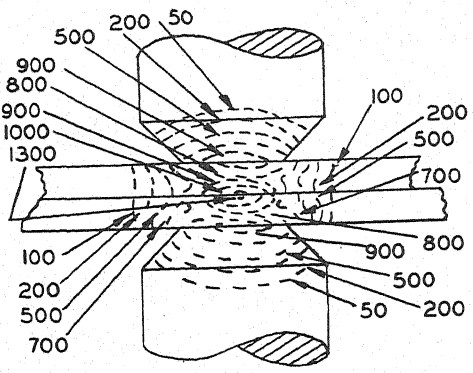


Fig. 3—Calculated Instantaneous Spot-Welding Temperature Chart in Degrees Centigrade

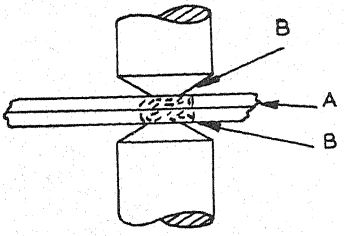
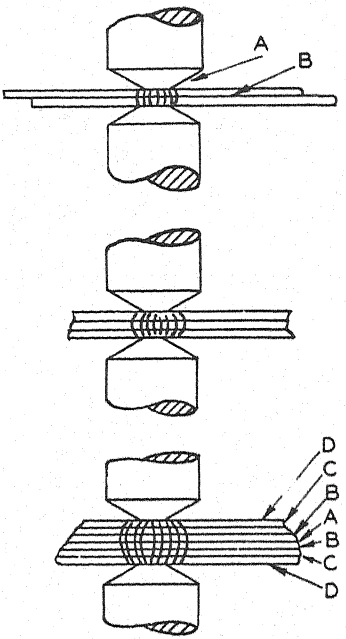


Fig. 4—Spot-Weld Heat Zone



Figs. 5, 6 and 7—Illustrating the "Fanning Out" of Current in Weld Metals—Spot Welding Two Thicknesses, Three Thicknesses and Six Thicknesses, Respectively

The tendency for the past several years has been toward higher current densities and shorter "current-on" time and will probably continue in this direction for some time yet. The advantages of speed and quality of work are obvious, but the disadvantages of increased cost of equipment and the availability of the required power must be recognized.

While previously we have considered the current to follow in straight lines along the path established by the tip surfaces, this is not exactly true, because the current will fan out in the weld metal as shown in Fig. 5. While the current density in amperes per square inch on the surface *A* is slightly less than for surface *B*, the contact resistance of surface *A* is so much greater than that at surface *B* that the fanning out effect can be neglected in most cases.

Figure 6 shows three thicknesses of metal between the electrodes, with the further fanning out effect. Figure 7 carries this still further with 6 thicknesses of metal. It will be seen that as the number of thicknesses increases the current density at the center contact surface *A* decreases. This

may easily be carried far enough for the center joint at *A* not to be welded at all, while joints *C* will be welded, with intermediate joints showing various amounts of weld.

Electrode Tip Size

The tip diameter (contact face) controls the size of the spot. If the diameter is too small, as shown in Fig. 8, the resultant spot is too weak, although it may be a sound weld. Another objection to small spots is that surface marking may be severe, and a small variation in tip diameter may result in large variations in spot strength.

On the other hand, if the tip diameter is too large the shaded center, Fig. 9, may get too hot, resulting in very poor appearance, and the weld be weak due to voids and blow-holes as a result of insufficient unit pressure.

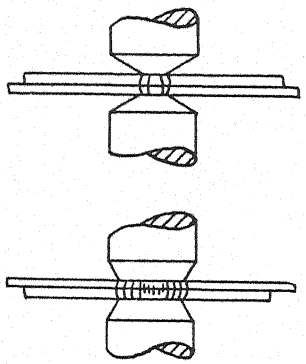
Data concerning proper tip size for various thicknesses of low carbon steel (0.05–0.15%) have in general been empirical and not always in exact agreement. However, most of the values are reasonably close to values which are obtained by using the following formula:

$$\text{Tip diameter} = (0.1 + 2t) \text{ in.}$$

where t is the thickness in inches of one thickness of the material to be welded.

The tip diameter thus bears a definite ratio to sheet thickness and the ratio is greater on thin sheet than on thick.

Reference to tip diameter should be interpreted to mean the diameter of the contact area between electrode tip and material at the conclusion of the welding. The diameter of the actual fused section between the two



Figs. 8 and 9—Illustrating Effect of Tip Diameter on Spot Welds

pieces of material will be slightly less than the diameter of the electrode contact area. In the case of 0.060-in. material, the weld area will be approximately 98% of the contact area. This percentage will decrease as material increases in thickness. For two pieces of $^1/_2$-in. material the weld area may be approximately 90% of the contact area. Based on the above formula, Table 1 gives values of tip diameter recommended and also the weld diameter which should be obtained under proper conditions of pressure, time and current for welding two pieces of steel.

Table 1—Values of Recommended Tip Diameters and Weld Diameters Obtainable Under Proper Conditions

Sheet Thickness, In.	Tip Diameter, In.	Tip Area, Sq. In.	Weld Area, Sq. In.
0.010	0.120	0.011	0.011
0.012	0.124	0.012	0.012
0.016	0.132	0.014	0.013
0.019	0.138	0.015	0.014
0.025	0.150	0.018	0.017
0.031	0.162	0.021	0.020
0.039	0.178	0.025	0.024
0.049	0.198	0.031	0.030
0.062	0.224	0.039	0.038
0.078	0.256	0.051	0.049
0.109	0.318	0.079	0.075
0.125	0.350	0.096	0.092
0.187	0.474	0.176	0.167
0.250	0.600	0.283	0.266
0.312	0.724	0.412	0.383
0.375	0.850	0.567	0.522

In the case of a piece of thin sheet welded to a piece of thick sheet the formula is still applicable. When selecting a tip size to contact the thin sheet, use Table 1, such as a 0.162-in. diameter tip for 0.03 in. and a tip size to contact the thick sheet as also indicated by Table 1, such as a 0.350-in. diameter tip to contact a sheet 0.125 in. thick.

Welding Pressure

When applied to the resistance welding processes, the term "welding pressure" has always been interpreted to mean "*static* welding pressure." As such, the measurement of welding pressure has been made by measuring the effort of an air or hydraulic medium in pounds per square inch on a piston of known area, or the effort of a spring and then adding the weight of the moving parts as determined by gravity.

An accurate analysis of the pressure exerted on the material during a spot weld will indicate that the effective welding pressure is *dynamic*, not *static*, and is materially affected by the friction and inertia of the moving parts of the welding machine.

Dynamic welding pressures are governed by five factors:

1. The pressure medium, i.e., air, hydraulic, spring.
2. Inertia, i.e., the total weight and distribution of weight of moving parts of the pressure system.
3. Friction in the pressure system.
4. Reaction on the pressure system by the "motor action" or "jump" of the current-carrying members during weld.
5. Strength under compression at various temperatures of the material being welded.

It has been fortunate for industry that mild steel with its wide plastic range can be welded with so many combinations of variables that for most practical purposes measurements of static pressure suffice as a yardstick of

dynamic pressure. Greater accuracy of measurement and attention to design detail are necessary when welding metals with a narrow plastic range.

Since the measurement of dynamic pressure for purposes of standardizing data used by the welding industry presents some major problems, all references in this discussion should be interpreted to refer to *static* pressure.

Such pressure may be measured by air or hydraulic gages, calibrated springs or balance weights.

Pressure so measured should be considered to meet the requirements of making a good weld with proper control of the other variables of spot-welding technique and welding material which is not so deformed previous to welding as to prevent a reasonably intimate contact at the weld zone with no welding pressure exerted.

For spot welding two pieces of low carbon (0.05–0.15%) steel of the same thickness, Table 2 gives values of recommended pressures when using the recommended electrode tip sizes recorded in Table 1.

Table 2—Values of Recommended Pressures Using Recommended Tip Sizes (See Table 1)

Sheet Thickness, In.	Tip Diameter, In.	Welding Pressure, Lbs.
0.010	0.120	100
0.012	0.124	120
0.016	0.132	140
0.019	0.138	150
0.025	0.150	275
0.031	0.162	300
0.039	0.178	375
0.049	0.198	475
0.062	0.224	600
0.078	0.256	750
0.109	0.318	1000
0.125	0.350	1300
0.187	0.474	2250
0.250	0.600	3000
0.312	0.724	3750
0.375	0.850	4500

The welding pressures in Table 2 are selected on the basis of giving optimum results with one continuous welding time of current flow. When welding with the pulsation type of current flow, lower pressures give satisfactory results particularly on material thicker than approximately 0.100 in. It is recommended that the pulsation type of welding be used in all cases when welding material heavier than that listed in Table 2 and in many cases when welding material thicker than about 0.062 in.

If the material to be welded is deformed so that the weld zone is not in intimate contact before current flow with very little pressure applied, values of pressure must be added to those required for welding to overcome the effect of the distorted material.

It is not considered best practice to use a technique which involves the cold deforming of the material to be welded before initiating current flow. However in some applications such practice may be deemed essential.

One authority lists the values shown in Table 3 as necessary to eliminate buckle. These values are to be added to the ones in Table 2 to arrive at the total pressure required for a given thickness of material.

Table 3—Additional Pressure Values Suggested to Eliminate Buckle

No. of Sheets	Thickness per Sheet, In.	Pressure, Lbs.
2	1/16	50
2	1/8	200
2	1/4	800
2	1/2	3,200
2	1	12,800

These data in Table 3 are based on the formula that the rigidity of the unrestrained sheets or plates increases directly as the square of the sheet thickness. Inspection of the pressure values shows how much more difficult it is to spot weld thick material than thin material when the material is deformed. It is easy to arrive at a condition where there is no material of proper conductivity which can be used for electrodes which will withstand such pressures for both deforming and welding.

As will be described in more detail under controls, the pressure cycle must be such that welding current is never applied without the material being under pressure.

Sustained pressure after current flow is ended is used in some applications of spot welding to minimize warpage of the welded structure by withdrawal of heat from the completed weld through the water-cooled electrodes.

Also in case deformed material has been forced together before welding, the delay in removing pressure until after the metal has become relatively cool gives the weld metal an opportunity to regain sufficient strength to resist fracture due to the "springback" of the deformed sheets.

Welding pressures for spot welding other materials than low carbon steel will be discussed later under the welding of the particular materials considered.

Welding Time and Currents

Considering the fundamental equation for the heat used to make a spot weld, i.e.,

$$H \text{ (expressed in watt seconds)} = I^2RTK$$

I = current flowing through the weld, in measured amperes.

T = time of current flow, in seconds.

R = effective resistance to current flow from one electrode contact area to the other in ohms.

K = factor representing losses by conduction, convection and radiation, being dissipated by the electrodes, work or surrounding medium.

The resistance is affected by specific resistance of electrodes and work areas, surface conditions, pressure, skin effect, temperature and perhaps other variables which will doubtless be more understood as a result of investigations now under way.

However for most practical purposes we may consider K, R and H as one unknown which we may designate as C. This reduces our equation to: $T = C/I^2$.

For any given set of conditions of material composition, pressure, electrode tip area, contact conditions, cooling medium, etc., which determine

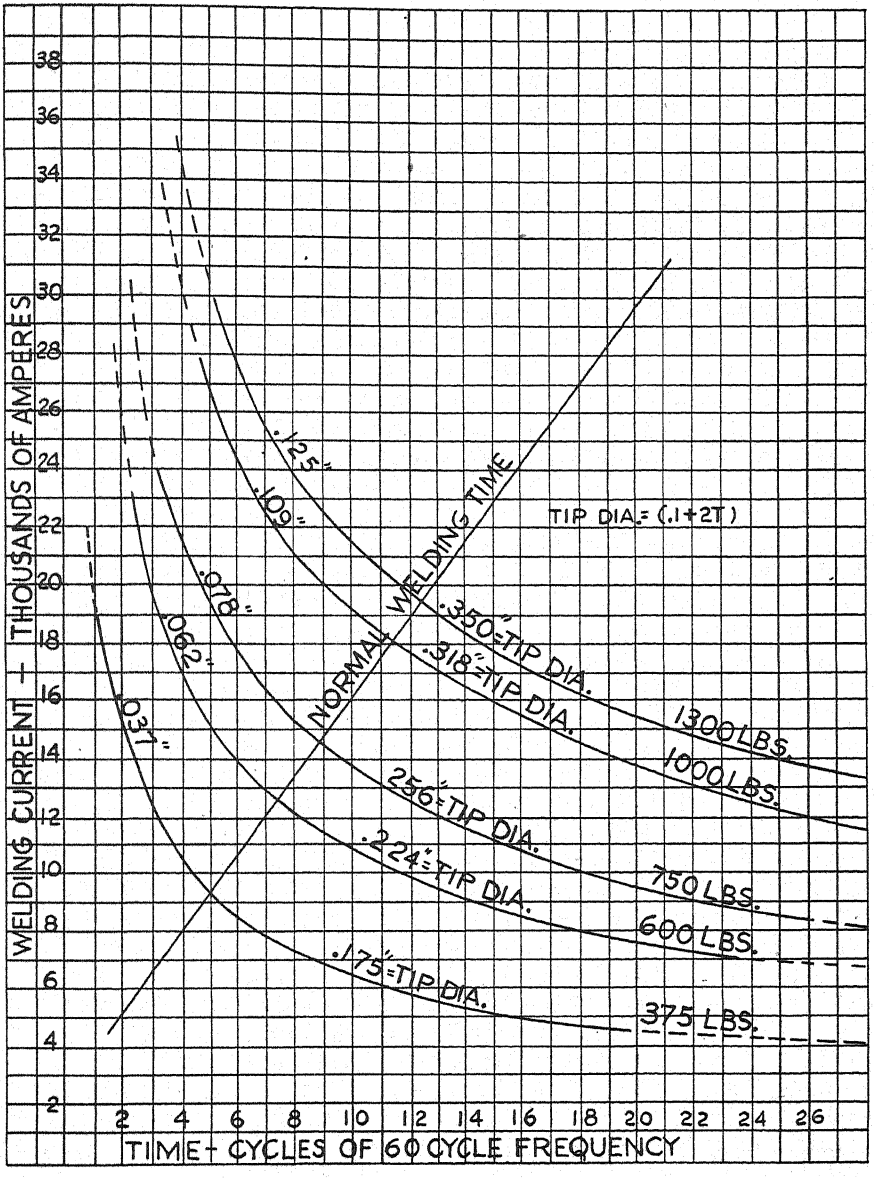


Fig. 10—Time and Current Curves—Equal Thicknesses, Clean, Low Carbon Steel

C, we can empirically determine the relationship of time and current. It is obvious from the equation that the plotted relationship will take the form of an inverse square curve.

When laying out a program for determining such empirical data it is obvious that a complete investigation would literally take innumerable

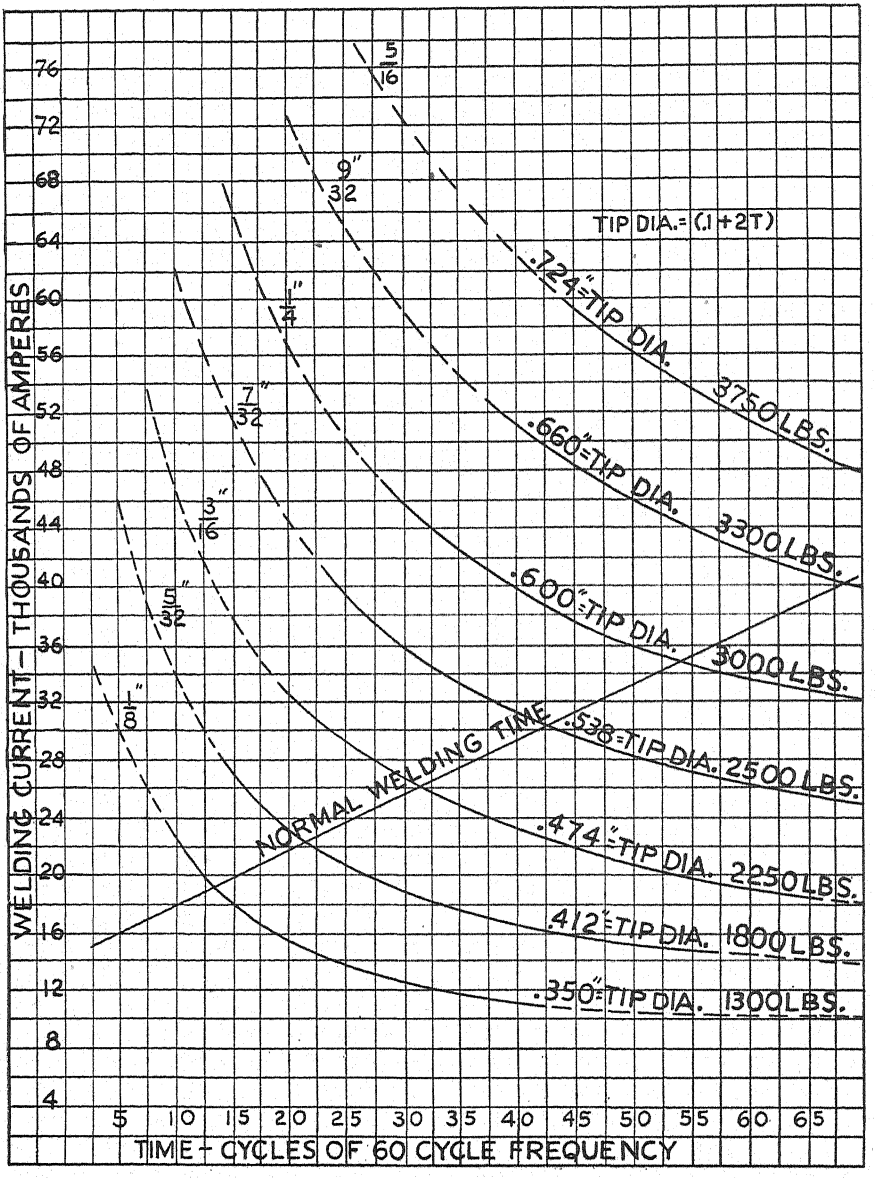


Fig. 11—Time and Current Curves—Equal Thicknesses, Clean, Low Carbon Steel

experiments. Therefore to obtain workable data the program was confined to the ranges of values known by experience to be reasonably practical.

The charts shown by Figs. 10 and 11 refer to welds which can be made on low carbon steel (0.10 to 0.20%), tip diameters as shown by Table 1 and welding pressures shown by Table 2.

It is not to be inferred in any way that welds cannot be made using other schedules. These schedules were set up on the basis of an optimum condition of spot strength and minimum of surface marking.

It is recommended that when selecting a schedule to use, such a schedule be as close as possible to the line marked "normal welding" through the knee of the curves. Best results will be obtained when working in this range.

Time and current values to be used for other materials than low carbon steel will be discussed later under the welding of the particular material involved.

Heat Balance

In the proper procedure for making a satisfactory weld there is a factor which is often not given its due consideration, mainly because of the difficulty in accurately predicting the exact effect. This factor is correct *heat balance.* The majority of discussions on spot welding are confined to the welding of two equal thicknesses of material with equal tip diameters. *Heat balance* in these cases is automatically correct. However, as probably 50% of practical applications do not have the above conditions, proper heat balance may mean the success or failure of a specific job.

Heat balance may be defined as a condition in which the fusion zones of both pieces of material to be joined undergo approximately the same degree of heating and pressure application.

Heat balance may be affected by:

1. Relative thermal and electrical conductivities of the materials to be joined.
2. Relative geometry of the parts to be joined.
3. Thermal and electrical conductivities of the electrodes.
4. Geometry of the electrodes.

It is desired, for example, to join a high copper content alloy of high thermal and electrical conductivity and material of low thermal and electrical conductivity such as stainless steel. In this case the weld may not be of the best quality due to a poor alloying condition of the dissimilar materials, but the nearest approach to a satisfactory weld would be by using one of the following techniques shown in Fig. 12.

Figure 12-A shows a correct heat balance obtained by using a smaller tip area on the copper alloy than on the steel alloy to obtain approximately equal fusion temperatures by variable current density.

Fig. 12-B shows a correct heat balance obtained by using an electrode with a facing of highly resistant material such as tungsten or molybdenum to create approximately the same heat in the copper alloy as in the steel alloy.

Figure 12-C indicates the use of a combination of both techniques shown by Fig. 12-A and B.

A proper heat balance may also be achieved in the two dissimilar alloys mentioned above by the method indicated in Fig. 13 where the increase in the thickness of the higher conductivity alloy compensates for the higher conductivity.

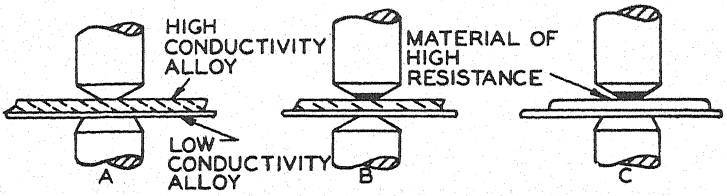


Fig. 12—Illustrating Different Techniques to Obtain Proper Heat Balance in Spot Welding High-Conductivity Alloy to Low-Conductivity Alloy

An artificial method of creating a heat balance sometimes consists in the use of a thin plating of lower conductivity material or the insertion of thin strips of such material between the two (2) pieces of work to be welded. Tin plating of copper or brass is an example of this technique. The plating is very thin, being measured in tenths of a thousandth of an inch.

Heat Shrinkage

It is often desirable to produce so-called invisible welds. This may be approximated if all factors are closely controlled. In order to attain the best results, it is necessary to understand the most important factor, that of heat shrinkage. When the work is heated, Fig. 14, it tends to expand in all directions, but due to the pressure exerted by the electrodes, any vertical expansion is immediately forged out, with the result that all of the expansion takes place in the horizontal plane, usually causing a slight ridge as shown at *A*, Fig. 15. In cooling, the contraction takes place along the lines of least resistance, or almost entirely in the vertical plane, which results in a concave surface as shown exaggerated in Fig. 15. This is not to be confused with electrode marks, where the electrodes imbed themselves into the work due to improper control. The actual depth of the depression is very little, usually not over a few thousandths of an inch, but in some forms of finishing operations it is very noticeable, especially with certain forms of light reflection. It is almost impossible to completely eliminate these heat shrinkage marks, but they may be materially reduced by proper control—that is, by making the weld in fast time, thereby preventing as much as possible the heat from radiating to the surface.

Various techniques are used to minimize these markings. The most common method is to use an electrode of greater area on the side of the material which is desired to have a minimum of marking (see Fig. 16). If this electrode is made of a copper alloy having a higher proportional

limit than that of hard rolled copper, the surface contacting the weld does not deform due to heat and pressure so quickly and so cause surface marking of the welded material.

One method which recognizes that the marking cannot be prevented entirely and that an imperfection can more readily be dressed off if it is above rather than below the material surface, creates such a condition by using a depression in the electrode contacting the depression surface to be

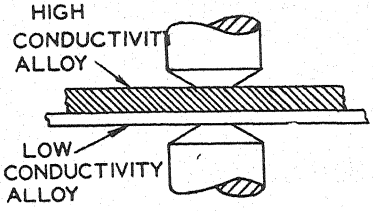
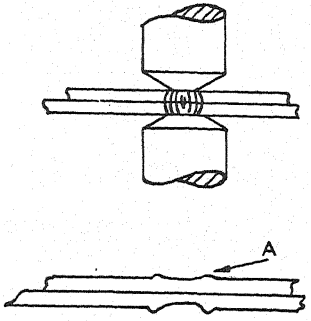


Fig. 13—Another Method of Achieving Proper Heat Balance in Spot Welding High-Conductivity Alloy to Low-Conductivity Alloy



Figs. 14 and 15—Illustrating Effects of Heat Shrinkage on Spot Welds

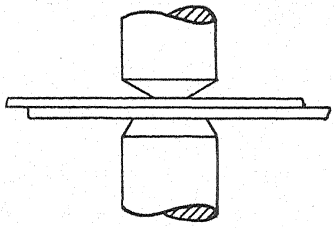


Fig. 16—One Technique to Minimize Marking on "Show" Side

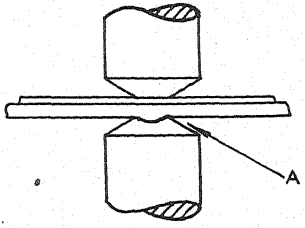


Fig. 17—Illustrating Use of Depression in Electrode to Deliberately Raise Surface of Metal to Be Later Removed to Produce Absolutely Smooth Finish on "Show" Side

finished, see Fig. 17 at *A*. The hot metal conforms to this depression and being above the surface of the surrounding material, is more easily dressed off.

Indirect introduction of current to the weld as shown in Fig. 18 assists in obtaining a minimum of marking on Part *B* by affecting current distribution in Part *B*.

Types of Spot Welds

Types of spot welds may be divided into two classes, namely, single welds

and multiple welds. These two classes may be further divided into direct and indirect welds.

A single spot weld may be defined as a weld made by current flowing through only one weld spot during any specific period of current flow. Figure 19 illustrates examples of single welds. Figure 19-C is considered a single weld even though multiple points are used, because sequencing

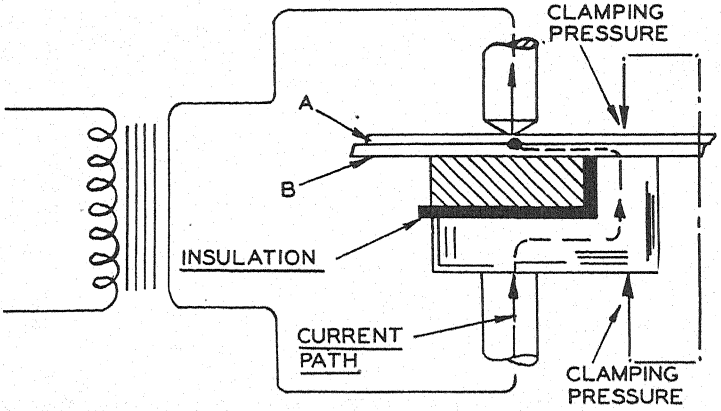


Fig. 18—Illustrating Effect of Indirect Introduction of Current to the Weld (Affecting Current Distribution) to Minimize Marking on "Show" Side

insures against simultaneous current flow through more than one weld spot. The illustrations in Fig. 19 indicate the distinction between direct and indirect welds for single welds and Fig. 20 for multiple welds.

Similarly multiple welding consists of making two or more spots simultaneously.

While applications of single and multiple spot welds follow the general theory of Figs. 19 and 20 the specific arrangements may vary.

Welds of the type as shown by Fig. 19-D, F and G and Fig. 20-L, M and O are often known as series welds and depend on an accurate knowledge of the relative resistance of the parallel paths available to current flow for their successful application. For example, in Fig. 19-D the dimension between contact points and the thickness of the materials must be such that a majority of the current will pass from the welding tip down through the spot to be welded, through the copper shorting block and back up through the contacting electrode rather than flowing through the upper plate between the contact points. A specific example may be cited where it was required to weld three thicknesses of $^{3}/_{32}$-in. thick low carbon steel in the manner illustrated by Fig. 20-L. Experiment determined it to be necessary to space welds on 6-in. centers to avoid excessive "shunting" of welding current. If closer spot spacing was desired, it would be necessary to "back-step," still keeping the electrodes on 6-in. centers.

While these illustrations have been shown using welding points for electrodes, circular wheels may be also used as electrodes for spot welding

with the possible exception of Fig. 20-O. In this case, the resistance of the wheel bearings would probably be too high for most applications.

Effect of Surface Conditions

In spot welding as in seam welding the condition of the surfaces of the material to be welded is of prime importance if quality results are desired.

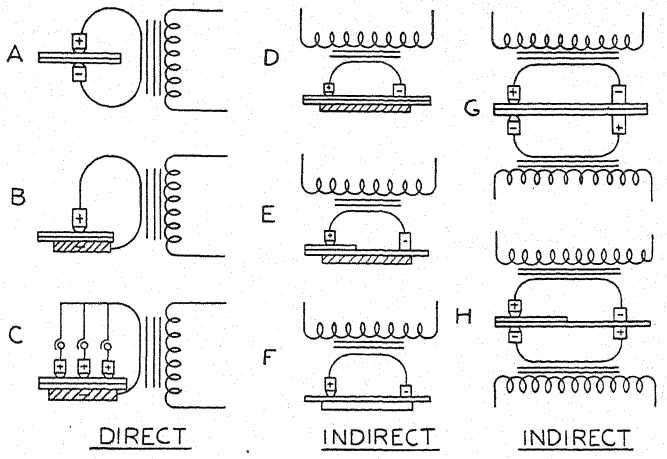


Fig. 19—Types of Single Welds

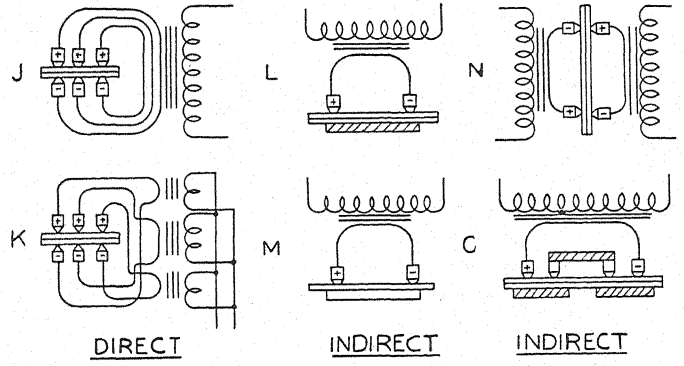


Fig. 20—Types of Multiple Welds

It is considered very poor practice to try to weld through grease, paint or steel scale and rust. A thin coating of oil does not seem to cause any very detrimental results but optimum quality of weld will be obtained if the material is degreased before welding. Hot rolled scale or annealing scale causes the majority of difficulties.

Improper surface conditions show up as gas inclusions or slag inclusions in the fused metal. Scale causes excessive burning and marking of the contacting surfaces of the steel with the welding electrodes.

Examination of a great many photomicrographs forces the conclusion that it is very seldom that commercial spot welds in gages heavier than autobody stock are free from slag and gas inclusions.

It has been found that even cleaning by steel shot or steel grit will create a condition where small particles of scale are driven into the surface of the steel and remain there through the welding operation.

The best way to clean steel for spot welding is to pickle thoroughly and immediately coat with a thin oil to prevent rusting.

The percentage of gas pockets increases with material thickness. Undoubtedly high welding pressures tend to squeeze out gas inclusions and, practically, unit pressures become less and less as the material thickness increases.

Strength of Spot Welds

It is difficult to get a consensus of opinion as to strength of spot welds or even how the strength should be measured.

However, average figures concerning welds made up to and including $^3/_{16}$-in. thick low carbon steel indicate that spot welds tested in shear, one spot tested at a time, will have a strength of approximately 45,000 psi., area of weld being based on the weld area at the faying or contacting material faces.

Direct tension tests made on single spot welds between U-shaped pieces indicate ultimate strength values of the order of 20,000 psi. with the weld area considered as the product of the thickness of one piece of material and the circumference of the weld at the faying surfaces of the material.

Welding High Carbon and Low Alloy Steels

Low carbon steel as discussed herein means a maximum carbon content of 0.20% and no alloying elements or high percentages of impurities. Typical of such steel is S.A.E. 1015 Steel.

High carbon steel as discussed herein refers to steels with a carbon content greater than 0.20% and still containing no alloying elements or high percentage of impurities.

The low alloy steels covered by this discussion may be said to be approximately defined as having the following limitation as to the maximum percentages of elements making up their chemical analysis:

Carbon	—0.15%	Copper	—1.50%
Manganese	—1.00%	Molybdenum	—0.20%
Silicon	—1.00%	Sulphur	—0.035%
Nickel	—1.50%	Phosphorus	—0.140%
Chromium	—1.00%		

These alloys are typified commercially by such trade names as "Ductiloy," "Yoloy," "Cor-ten," "Dyn-nel," etc.

Comparing the welding of high carbon and low alloy steels with low carbon steels brings forth the following differences in welding schedules:

(*A*) Welding currents for the high carbon and low alloy steels should be approximately 90% of the currents required for low carbon steel due to the higher resistivity of these materials.

(*B*) The high carbon and low alloy steels are more sensitive as to the exact time and current values used than are low carbon steels.

(*C*) Welding pressures approximately 10% greater than are used for low carbon steels should be used for welding the high carbon and low alloy steels. This is due to the greater compressive strength to be overcome when forging during a spot weld.

(*D*) The welds made on low carbon steels are much less embrittled by welding than welds made using high carbon and low alloy steels.

(*E*) When welding these materials using time and current ratios as determined by Figs. 10 and 11 it is advisable to use values selected well to the right of the normal welding line. The reason for selecting long welding times is to retard the quenching rate of the heated metal and so reduce the degree of embrittlement which would otherwise be obtained.

As a typical example, much less embrittlement will be obtained when welding two thicknesses of $^1/_8$-in. low alloy steel if the welding time is 70 to 90 cycles instead of 15 to 20 cycles.

These materials may easily embrittle to a degree of 100% greater hardness through the heat-affected area than low carbon steel welded using the same short-time schedules.

(*F*) These materials are more subject to "flashing" or "spitting" and also to excessive indentation than the low carbon steels. This is due to the higher resistivity and more critical nature as to time-current ratios. The use of long welding times to retard embrittlement has a tendency to increase indentation due to a greater degree of surface softening of the material.

Reference is made to Chapter 18 for further information on the low alloy steels.

Plated and Coated Steels

Plated and coated steels can be successfully spot welded, the welding characteristics for which will largely be the same as for the low carbon steel base.

Terne Plate and Tin Plate.—These plated steels can be spot welded with no difficulty, using somewhat larger currents than for same thickness of steel. In the welding operation, however, the lead and tin coatings will fuse into the steel base on the inside surfaces. The coating on the outside surfaces, however, need not be seriously damaged. Ordinarily, there will be sufficient heat to melt that metal directly under the electrodes, but the time and current should be controlled so that there is no melting of the coating in the area outside the electrode tips. Also, full electrode pressure should be maintained after the welding until the stock has cooled below the melting point of the tin or lead coating. This means a longer "hold" time than is used for uncoated steels. Flat tipped or dome faced electrodes should be used, to prevent or minimize indentation. Welds made in this manner leave the plated surfaces clean and bright, and none the worse for the weld, although the electrode marks are visible. This is seldom an objection, however, because this material is seldom put to any finishing operation.

Galvanized Steel, Galvanneal and Zinc Plated Steel are welded in much the same manner as terne and tin plate. Due to the narrow range between the melting and boiling points of the zinc coating, heavier pressures should be used on this material to reduce vaporizing the zinc. Welds in this material

are satisfactory in every respect, although in the heavier gages (about 14 gage and over), it is very difficult to prevent partial destruction of the zinc coating in the area immediately surrounding the tips. Close control and sufficient machine capacity, both electrical and mechanical, will minimize this effect. Where this is an important factor, both pressure and current allowance should be increased 25 to 50%.

Chromium Plated Steel is not as successfully spot welded as the other platings just described, for two reasons. First, since the primary object of chromium platings is to secure a high polished finish, any markings whatever are objectionable. Second, chromium plate is exceedingly thin, from one to five ten-thousandths of an inch thick, which eliminates any possibility of finishing operations after welding. Aside from the marring and partial destruction of the plate, this material welds with about the same time current and pressure as ordinary steel. The quality of the weld will be no better than the bond between steel and plating and such bond varies widely with commercial plating.

Nickel Plated Steel presents much the same problems as chromium plate, but nickel plate is heavier (usually about 0.001 in. thick), and consequently provides more leeway for finishing after welding. Electrodes of high conductivity should be used for both nickel and chromium plated steel.

High Alloy Steels

For information on this subject see Chapter 19.

Copper and Copper Base Alloys

At the beginning of this chapter the general principles underlying spot welding were outlined and it was pointed out that the electrical and thermal conductivity of the weld metal largely determined its weldability. Table 4 of this section tabulates most of the commercial copper base alloys, with their approximate analysis, electrical and heat conductivity, and a welding index classification. Both the electrical and heat conductivity are expressed as a percentage of that of pure copper. The letter prefix of the welding index designates its weldability status, thus, A is clean low carbon steel, and is the basis of comparison. B indicates that this alloy welds nearly as easily as steel; C, next in line, etc., up to G, which class includes those which can be welded successfully, but 100% uniform results cannot be expected, or, in other words, a certain percentage of defective welds should be expected. H includes the class which is considered commercially impractical to spot weld. Into this class also falls pure silver. The numbers following the letter indicate the relative secondary current required. This is a percentage of the capacity required for the equivalent section of low carbon steel. Thus, Herculoy may be easily welded. The machine should deliver 25% more current than for the same thickness of steel. In practically all cases the welding time should be shortened, that is, use time values to the left of the normal welding line in Figs. 10 and 11. The shorter time accounts for part of the increased current required.

The application of this table must not be taken too literally. It is intended as a guide only, and in no sense as an absolute statement of the welding properties. The welding index ratings are based on general ex-

Table 4—Spot Welding Data for Copper and Copper Alloys

Material	Approximate Analysis, %					Electrical Conductivity	Heat Conductivity	Welding Index
	Copper (Cu)	Zinc (Zn)		Lead (Pb)	Tin (Sn)			
Copper	99.9	...	...	...	...	100	100	H-500
De-oxidized Copper	99.9	...	...	...	...	...	...	H-500
Commercial Bronze, 95%	95	5	...	...	...	55	62	H-200
Commercial Bronze, 90%	90	10	...	...	...	41	48	H-200
Red Brass, 85%	85	15	...	...	...	37	41	H-200
Red Brass, 80%	80	20	...	...	...	32	36	G-175
Brazing Brass	75	25	...	...	...	30	34	G-150
Spring Brass	72	28	...	...	...	29	32	E-150
Cartridge Brass	70	30	...	...	...	28	31	E-150
Cartridge Brass	69	31	...	...	...	28	31	E-150
Eyelet Brass	68	32	...	...	...	27	31	E-150
Drawing Brass	66.7	33.3	...	...	...	26	31	E-150
Yellow Brass	65	35	...	...	...	27	31	F-150
Yellow Brass	63	37	...	...	...	26	31	F-150
Muntz Metal	60	40	...	...	...	29	33	F-150
Cap Gliding	90	9.6	...	0.4	...	42	...	...
Butt Brass	64	35	...	1	...	...	...	...
Clock Brass	61.5	37	...	1.5	...	...	...	...
Oreide	87.25	11.50	...	...	1.25	...	...	...
Admiralty	70	29	...	...	1	25	28	...
Tobin Bronze	60	39.25	...	...	0.75	25	30	F-150
Govt. Naval Bronze	60	39	...	0.25	0.75	25	30	F-150
Special Bronze	98.75	...	...	...	1.25	43	56	G-200
Phosphor Bronze, A	96.25	...	...	...	3.75	13	16	D-125
Phosphor Bronze, *A*—5%	95	...	...	...	5	18	31	D-125
Phosphor Bronze, *C*—8%	92	...	...	...	8	13	16	D-125
Phosphor Bronze, D	89.5	...	...	...	10.5	11	13	D-125
20% Cupro Nickel	80	...	Ni—	20	...	6	9	C-125
15% Cupro Nickel	85	...	Ni—	15	...	8	12	C-125
30% Nickel Silver	47	23	Ni—	30	...	4	...	C-125
Super Nickel	70	...	Ni—	30	...	5	8	C-125
Ambrac B	65	5	Ni—	30	...	4	7	C-125
25% Nickel Silver	55	20	Ni—	25	4	4	...	C-125
Ambrac A	75	5	Ni—	20	...	6	10	C-125
18% Nickel Silver	65	17	Ni—	18	...	6	9	C-125
18% Nickel Silver	55	27	Ni—	18	...	6	...	C-125
15% Nickel Silver	64	21	Ni—	15	...	6	9	C-125
10% Nickel Silver	65	25	Ni—	10	...	8	12	C-125
Nickel Silver, 5%	62	33	Ni—	5	...	12	15	C-125
Manganese Bronze	59	39	Fe—	1.25	0.75	25	26	C-125
Herculoy A	96.25	...	Si—	3.25	0.5	9	9	B-125
Herculoy B	97.75	...	Si—	2	0.25	12	13	B-125
Special Silicon Bronze	78	21	Si—	1.0	...	13	...	B-150
Ambroloy, 5%	95	...	Al—	5	...	18	21	C-125
Ambroloy, 8%	92	...	Al—	8	Mn	15	19	C-125
Everdur A	96	...	Si—	3	1.0	7	8	B-125
Everdur B	98.25	...	Si—	1.6	0.5	12	14	B-125
Hitenso A	99.35	...	Cd—	0.6	...	85	...	H-400
Hitenso BB	99	...	Cd—	1.0	Sn	80	90	H-400
Hitenso C	98.6	...	Cd—	0.8	0.6 Ni	55	60	H-300
Beryllium Copper	97.4	...	Be—	2.25	0.35	20	25	C-150

perience. No ratings indicate lack of experience concerning the alloys; as more information is collected, the blanks will be filled.

As was pointed out earlier in this chapter, a spot weld is made by virtue of the generation of heat in the relatively high-resistance work between the electrodes. Copper, however, has no higher resistance than the electrodes, and by reference to Fig. 5, it will be seen that the actual current density at *B* is less than at the electrode tips, *A;* therefore, if we expect to obtain a weld at *B* we should also expect one at *A*, which is exactly what happens. Copper can be partially welded with the use of tungsten or molybdenum tips, in which case surface *A* gets much hotter than *B*, but since copper cannot weld to tungsten or molybdenum no weld takes place at *A*. However, the outside surfaces due to the very high temperatures are so badly damaged that the resultant weld is weak, porous and generally unsatisfactory. Another objection is the high-electrode maintenance cost. All the above remarks apply equally to silver which has a thermal and electrical conductivity of 103%. The atmospheric film of both metals is ineffective in materially aiding welding. In some instances a thin coating of tin on the faying surfaces has produced welds adequate to the purpose for which they were used.

In order to have a proper understanding of the welding characteristics of the copper alloys, it is necessary to know something of the nature of these alloys and the effects of the various alloying elements.

In general, brass is an alloy of copper and zinc, and bronze is an alloy of copper and tin; however, due to the various combinations of alloying elements, there is no distinct classification of the two. The principal alloying elements, in order of their importance, are: zinc, tin, nickel, silicon, aluminum and beryllium. Others, such as manganese, lead, cadmium, silver, phosphorus, etc., are also used. The effects of each of these will be briefly outlined.

Zinc.—Practically all brass is composed of copper and zinc, in combinations ranging from 85–15 to 50–50. The effect of the zinc is to lower the electrical and heat conductivity. Zinc melts at 786°F. and boils at 1706°F. and since the melting point or welding temperature of brass is from 1750 to 1900° there is some tendency for the zinc to vaporize and form a zinc oxide on the surface. (See also Spot Welding of Galvanized and Zinc Plated Steel, page 335.)

Pressure employed for welding copper alloys is extremely important. This is especially true with brass of the higher conductivity alloys. The current required for welding brass varies over wide limits directly in proportion to the pressure. Probably one of the simplest and best ways to set up a welder for brass is to adjust the current to a high value and the pressure also high. Then reduce the pressure until satisfactory welds are made. Next, reduce both current and pressure in steps without sacrificing weld strength. This should not be carried too low, however, because in that case the welds will not be uniform.

Timing is very important for brass. It is believed that the metal welds with the first few cycles of current. Further application of current generates less heat due to the fact that the high-resistance film has disappeared, and probably the heat is conducted away as fast as it is generated.

Alloys that have increased strength due to cold working should be welded as fast as possible to reduce the area annealed by the weld.

Tin.—Tin, alloyed with copper, reduces the thermal and heat conductivities much more than does zinc. Thus, $1^3/_4\%$ tin reduces these conductivities more than does 15% of zinc, so that the bronzes generally have more resistance and are, therefore, more readily welded than the brasses. Furthermore, while tin melts at 450°F., its boiling point is 4100°F.; it consequently does not vaporize and form surface oxides. Electrode pressure should be light, but, probably due to the higher inherent resistance, tin alloys are not so sensitive to pressure as brass.

Most of the modern tin bronzes, except the cast bronzes used for bells, are deoxidized with phosphorus with 0.01 to 0.30% residual in the metal. This phosphorus will, in the welding heat, vaporize from the metal and deoxidize the surfaces in contact with the electrodes causing the latter to stick. This means pickup of the metal on the electrode and frequent loss of time for redressing. For satisfactory welding properties, the tin bronzes should be near the low limit in phosphorus or be deoxidized with some other element as zinc or silicon.

Nickel.—The addition of nickel to copper reduces the conductivity very rapidly, putting these alloys, commonly known as nickel silvers, in a preferred welding classification. These alloys are commonly used for jewelry, instruments, architectural trim, electrical resistances, etc. It will be noted from the tables that the resistances of this group are greater than for steel, and it might be assumed that it is easier to weld than steel, and therefore requires less welding capacity. However, unlike steel, practically all non-ferrous metals have a very narrow temperature range in which they will weld. It is, therefore, necessary to use shorter time than for steel to prevent severe indentation. It is this short-time factor that is responsible for increasing the current required.

Nickel is soluble with copper in all proportions, and is probably used in wider alloying percentages than any other metal. Alloys containing over 50% nickel are classed as nickel alloys and treated in Chapter 24.

Silicon.—Silicon, up to about 3% alloyed with copper, forms one of the most important groups of metal—silicon bronze. This group is better known by its trade names: Everdur, Herculoy, Olympic Bronze, etc. On account of its high resistance, it ranks first among the copper base alloys in weldability. In its varieties, which are somewhat similar in properties, it is widely used for tanks, corrosion-resisting linings, refrigerator evaporators, etc., and consequently has more resistance-welded applications than any other copper base alloy.

All surfaces should be chemically clean before welding. Copper silicon alloys will not weld properly if scale or heat tarnish is present. Since the silicon does not vaporize but forms a refractory dielectric film, there is no trouble from pickup. Pressures employed are slightly less than for steel and the timing should also be less than for steel.

Aluminum.—Aluminum bronze at the present time is chiefly used in the cast or extruded form although it is also available in rolled forms. It falls slightly below silicon bronze in weldability, and the schedules used for silicon bronze are generally satisfactory for aluminum bronze.

Lead.—Alloys containing appreciable amounts of lead are generally

unsatisfactory for welding and should be avoided. It is insoluble in copper, existing only as a mixture, and sweats out at its melting point, 621°F. Probably the principal application of rolled leaded alloys is for bearing linings (88% copper, 4% zinc, 4% tin, 4% lead). Since it has practically no welding applications, actual information is lacking.

Beryllium.—This element alloyed with copper has a great influence on its mechanical properties. It is a copper base alloy that can be heat treated and as such, the tensile strength exceeds that of mild steel and is comparable with some of the alloy steels. Cold-rolled heat-treated beryllium copper attains a tensile strength of 190,000 psi. Due to the fact that its maximum properties can only be obtained through heat treatment, which is generally impracticable on resistance-welded assemblies, its welding index is moderately high due to the short time recommended.

General.—The following conclusions may be drawn on welding characteristics of the copper base alloys:

1. Their electrical and thermal conductivities are a good gage of their relative weldability in an inverse ratio and of the secondary current required.

2. Welding pressures are somewhat lighter than for steel and in the case of the high brasses are considerably lighter. Welding machines used for welding all copper and nickel alloys should have pressure systems with such dynamic characteristics as to "follow-up" quickly as the weld metal melts. This means low inertia and low mechanical friction.

3. The welding time is shorter than for common steel, but comparable to that for stainless steel. While synchronous electronic tube timing is not essential for good results, it is recommended.

4. Reference is made to Chapter 22 for further information on these materials.

Nickel and High Nickel Alloys

For information on the resistance welding of these materials see Chapter 24.

Tin—Lead—Zinc

Some authorities class tin and lead as weldable metals. It is assumed, however, that due to their low melting points, a commercial application would offer considerable difficulty.

Zinc can be spot welded, but as previously pointed out, due to the narrow range between the melting and boiling points, considerable interference is caused by the metal vaporizing, although this is not so pronounced in spot welding as in seam welding. Fractured welds show a pronounced crystalline structure.

However, slight variation in surface scale materially affects weld strength with the result that uniform welds are difficult to obtain.

Lead can best be spot welded using tungsten or molybdenum electrodes and the bond is more a melting due to the heat of the electrodes than due to the heat created by the resistance of the material itself.

Tungsten, Molybdenum and Tantalum

The metals tungsten, molybdenum and tantalum are usually classified

as refractory metals because they are all characterized by having extremely high melting points, the melting point of tungsten being 3380 °C., of molybdenum 2620 °C., and of tantalum 2850 °C.

In resistance welding, the metals are joined together by providing heat generated by the passage of a high electrical current and with the application of pressure a weld is formed between the two materials to be welded. In certain metals actual fusion at the interfaces is necessary to produce a substantial weld, while in other metals welding may be due to a recrystallization process taking place below the melting point of the metal. There is reason to believe that in the case of the high melting point materials, tungsten, molybdenum and tantalum, welding is produced by a recrystallization between the metals.

Due to the high melting point of the refractory metals they are prepared by means of powder metallurgy and their ductility is provided by a fibrous structure which has to be retained during welding in order to provide a certain amount of ductility combined with high strength in the weld area. For this reason, it is necessary that the materials be welded with the shortest possible current duration period or current timing. In actual practice, these materials when used in the form of wires, thin sheet or small parts are best welded by means of a percussive welding process. This process consists essentially of a bank of capacitors which is charged to a relatively high potential and suddenly discharged through the parts to be welded, resulting in an extremely high welding current of very short duration.

Recently considerable improvements have been made in percussive welding equipment whereby more accurate control of the welding current impulse is provided. The extremely short welding current impulse provided by percussive systems avoids excessive recrystallization of the refractory metals being welded, thereby avoiding brittleness in the weld.

Furthermore, the refractory metals tungsten, molybdenum and tantalum oxidize readily when heated to elevated temperatures in the presence of air. The extremely short weld time provided by percussive systems eliminates to a large extent oxidation of the materials.

Conventional a.c. spot welding has been found suitable in many cases for welding the refractory metals and is particularly recommended if the current duration period is accurately controlled by means of a synchronous electronic tube control. Satisfactory results have been obtained in both spot and seam welding of tantalum, and both tungsten and molybdenum have been spot welded on a.c. welders without encountering excessive recrystallization if the proper welding conditions are used.

In order to reduce oxidation and to decrease electrode deterioration the refractory metals have been satisfactorily welded under certain liquids such as carbon tetrachloride and water. Oxidation may also be avoided by playing a stream of hydrogen on the parts being welded. It has been found that tantalum and molybdenum have slightly better resistance-welding characteristics than tungsten with regard to brittleness in the weld area.

In many cases it is desirable to attach by resistance welding tungsten, molybdenum and tantalum to other materials such as iron base alloys, copper base alloys or nickel alloys. Refractory metals form alloys with

iron, cobalt and nickel quite readily, while on the other hand, it is difficult to form alloys of the refractory metals with copper or silver. However, it seems possible to obtain, by proper welding conditions, a wetting of the refractory metals with copper or copper base alloys and thereby produce a satisfactory "stick" weld. In welding refractory metals to iron and nickel alloys directly, usually these lower melting point materials fuse at the weld interface, thereby wetting the refractory materials and forming small surface alloy layers.

In many cases in welding the refractory metals to each other, it has been found desirable to interpose between the two metals a third metal, such as nickel or nickel alloy, or similar materials which alloy readily with both refractory metals to be joined together. It has been found possible also to use straight butt welding for attaching refractory metals to base metals such as iron and nickel base alloys.

The strength of the joints obtained using proper timing, pressure and heating is in the neighborhood of 35,000 to 50,000 psi. Welds of greater strength and consistency may be obtained by employing a flash butt-welding method in place of the straight butt-welding method.

Spot Welding Aluminum Alloys

See Chapter 23.

Spot Welding Magnesium Alloys

Welding Tips.—Welding tips for use on magnesium alloys are very similar to those used with aluminum and its alloys. As with aluminum, electrodes should have an electrical conductivity of 80% or better, a Rockwell hardness of B60 or more, and high resistance to deformation at high temperature.

Either tapered or threaded tips are satisfactory. The threaded tips usually, but not necessarily, have a greater cooling area and greater diameters. This is important on magnesium alloys due to the high current values employed.

Electrode Faces.—Many types of electrode tips have been recommended by various authorities, but for general use it is believed plain spherical faced tips having (approximately) 2 in. to 4 in. radius, give best results. They are much easier to maintain both from the standpoint of cleaning with abrasives and from changes in contour due to pressure and heat during welding.

Flat tips and truncated cones should be used only when care is exercised that the plane of the tips and the sheet are perfectly parallel.

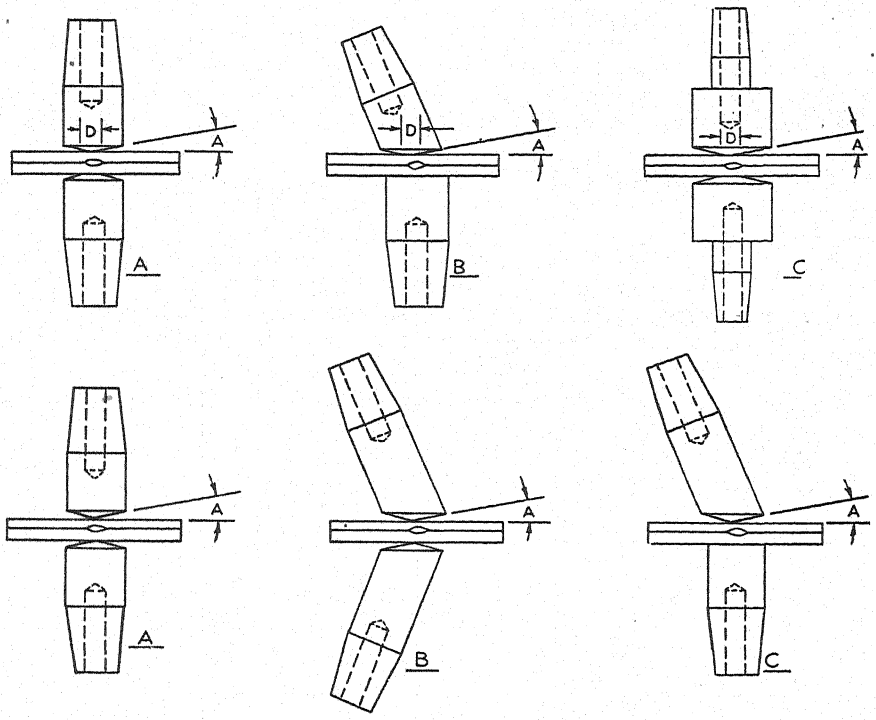
When using cone tips, the included angle should be 166–177° (4° and 3° cones). With the larger angle, the penetration is greatly reduced and the fused zone is larger giving better strength. The contour of the 3° cone is much easier to maintain (see Figs. 21 and 22).

Care of Electrodes.—The contact surface of the electrode tip should be maintained in the best possible condition. 2/0 to 4/0 emery paper produces a good finish. A sponge rubber backing may be used to cause the paper to follow the contour of the tip. Steel wool and coarse emery paper

should not be used, for a rough electrode surface increases tip pickup and tip alloying with the magnesium surface.

Cleaning with fine polishing paper will usually be necessary after 10–30 spots. When welding thick material the pickup will be more rapid due to the higher currents necessary and the higher temperatures produced at the contact surface of the electrode and magnesium alloy.

To produce highly consistent welds all cleaning should be done either in a jig or in a lathe where proper care of tip contour can be taken. This is not nearly as necessary when using quite large radius electrodes as with one or flat tips.



Figs. 21 and 22—Illustrating Conical and Flat Tips for Aluminum and Magnesium Spot Welding

In all cases, the electrodes should be water cooled for best results. Hot tips not only add resistance to the circuits, reducing the current, but cause pickup and alloying of the magnesium surface.

Tip pickup greatly increases the corrosion rate of the spots on magnesium alloys. Mechanical cleaning of the spots as by grinding will remove the effect of burned spots.

Preparing Surfaces for Welding.—Magnesium surfaces both in contact with the electrodes and each other should be free of any but a superficially thin oxide film. This may be accomplished by using a fairly fine wire brush or by using polishing compounds such as Lea grade L, C and S on a buffing wheel.

Very good tension results may be obtained when chrome-pickled interfaces are used, but the spot strength tends to be erratic and the fusion zone more porous. There is also a tendency for "flashing," or "spitting." When welding chrome-pickled surfaces, either higher pressures or lower currents must be used than for polished sheets. The chrome-pickle coatings vary in electrical characteristics, thereby affecting the machine settings. Trial runs are usually necessary to determine correct settings.

In general, for consistent weld strengths, all surfaces should be mechanically cleaned if possible. The cleaned magnesium may be exposed to a relatively dry atmosphere for several hours if necessary without requiring a change of the machine settings.

Welding Machines.—Both the conventional a.c. and the d.c. stored-energy type machines have been successfully used on magnesium alloys. When using the a.c. type, some kind of precision synchronous timing device must be used. Adequate current capacity with provision for adjustment of each of the machine variables is essential. Timing should be precisely adjustable for 1–20 cycles. Air-operated equipment for determining pressure must be accurate and adequate, extending over a range of 100–2000 lb.

Both the electromagnetic and the condenser discharge type stored-energy welders have been successfully used for spot welding magnesium. Present indications are that both good strengths and consistent welds can be produced using these types of equipment, but the data are incomplete at present so machine settings and weld strengths cannot be given.

Machine Settings for Magnesium Alloys.—The exact settings required on a machine for welding magnesium alloys cannot be given due to the great effect of surface finish and tip size. When 3° cone tips are used on a magnesium +1.5% Mn alloy with a wire-brushed finish the settings given in Table 5 may serve as a guide to the determination of correct procedure when using a.c. machines:

Table 5—Machine Settings for Magnesium Alloys

Sheet Thickness, In.	Electrode Pressure Range, Lb.	Weld Time in Cycles Range	Welding Current, Amp.
0.020–0.020	200–500	1–4	10,000–17,000
0.040–0.040	400–700	5–8	20,000–25,000
0.064–0.064	600–900	9–12	25,000–30,000
0.081–0.081	800–1200	12–16	30,000–35,000
0.128–0.128	1000–1500	16–20	35,000–45,000

For alloys other than the above, lower pressures and heats must be employed. In all cases, the exact setting must be determined for different type set-ups and for individual machines.

Increasing the "current-on" time increases the diameter and amount of fusion of a weld, as well as its homogeneity. Apparently a weld starts at certain points and, with increase in "current-on" time, these centers become a single globule of fused metal. Original holes in the weld are eliminated with time of current passage and the resulting spot is more uniform.

At low values of "current-on" time and low currents in welding thick sheet, blow-holes may form near the center and extend radially to the edge. Even with high pressure (but short time) these holes will still remain but are eliminated by increasing the cycles. Low pressures and high currents also tend to form blow-holes. Shear data fail to show any effect of fine porosity located near the center of the weld.

Spots made through the chrome-pickle finish will have satisfactory shear strengths if the proper values of current, pressure and time are used. The pressure is 200–300 lb. higher than with mechanically cleaned sheets, and the time may have to be increased to reduce porosity and get more uniform spots.

Spacing of Spot Welds.—Table 6 shows the minimum recommended distances that spot welds should be from each other to avoid shunting through the preceding weld. Minimum recommendations for spot to edge distances are also given.

Table 6—Spacing of Spot Welds in Magnesium Alloys

B&S Gage	Spot Spacing, In.	Edge Distance, In.
24	0.5	0.125
18	0.75	0.187
14	1.0	0.250
12	1.25	0.375
8	1.5	0.625

Strength of Spot Welds.—The strength of spot welds in magnesium alloys, as with other metals, is greatly affected by many variables such as tip shape, pressure, current dwell and alloy content. Table 7 gives typical values for the alloys shown. These values were obtained by using 3° cone tips on an a.c. type welder. Equal thicknesses of wire-brushed sheet were welded.

Table 7—Strength of Spot Welds in Magnesium Alloys

Thickness Single Sheet B&S	Thickness Single Sheet, In.	Breaking Load in Single Shear, Lb./Spot	
		Mg + 1.5% Mn	Mg + 6% Al + 0.2% Mn
24	0.020	100	130
18	0.040	300	350
14	0.064	550	725
12	0.081	700	1000
8	0.128	1200	1600

The shear values vary greatly with the spot diameter and to a lesser extent with the thickness of the fused material. The weld should constitute 60–75% of the thinnest section involved in the weld.

Tests have shown that both shear and tension values can be materially increased by annealing the welded sections for one hour at 600°F.

An excellent qualitative test for spot welds is given by tearing the welded sections apart and examining the spots. A button should be torn in one or the other sheets. With a little experience a very close approximation can be made of the shear strengths by the weld diameter and general appearance.

PROJECTION WELDING

General Principles of Projection Welding

Projection welding is a method of resistance welding by which the current flow and heating during welding are localized at a predetermined point by the design of the parts being welded. This is usually accomplished by a projection, or embossment, on one or both of the work pieces and thus derives its name.

Advantages of Projection Welding

This method has many advantages, some of which are:

1. Increased output for each stroke of machine, since a number of welds may be made simultaneously.
2. Longer electrode life, because electrodes with large contacting surfaces may be used, pressure and current being localized by the projection, or embossment.
3. In some instances, parts may be projection welded which could not be welded by other resistance welding methods. For example, irregularly shaped forgings or irregularly shaped thick pieces.

Applications of Projection Welding

As in the press working of metals, the application of projection welding is limited only by the ingenuity of the designer. The principal uses of projection welding are those in which punched, stamped or formed parts are assembled, the embossments being formed during the stamping operation. The projection is usually circular in shape, but may be of almost any regular design. The circular shape, however, has advantages, both in welding and also in the simplicity of punch and die design.

Projection welding is also applicable to the use of screw machine parts, the projection being turned on the screw machine part by means of a form tool. This part may be used in connection with a stamping or a flat or formed sheet, in order to obtain the assembled piece.

Cross-wire welding, which is used extensively in making wire mesh and other forms of wire products, is a form of projection welding and the general factors which affect projection welding also apply to cross-wire welding.

In addition to the above, there are specialized applications of projection welding, such as welding bolts and nuts, which may be obtained with projections cold forged in place.

Size and Shape of Projections

The size and shape of the projection are not fixed by theoretical limitations, but have been determined by practice over a period of time. Experience has indicated that projections of the form shown in Fig. 23 are satisfactory for most work in flat or irregular stampings. Instead of round, projections may be of oblong shape, square, oval or any shape which may be conveniently made, but it should be remembered that, in a carefully de-

signed projection, the weld grows from the center outward and that, to obtain a uniform growth, the round projection is theoretically desirable. Because of the wide plastic range of steel, almost any shape within reason may be satisfactorily welded, provided the welding conditions are properly maintained, but the most trouble-free projection, when welding flat pieces or where the projections contact flat pieces, is the round form.

When projections are to be made on formed pieces which are circular, or not flat where the projection contacts the piece, it may be desirable to elongate a projection to make certain that proper contact is obtained. Such a design of projection for curved pieces is shown in Fig. 24. It is always desirable to start with a point of contact from which the weld may grow, rather than to attempt to contact a plane surface against another plane surface. This latter usually results in point contact and this contact may be at some point which would not permit obtaining a complete weld.

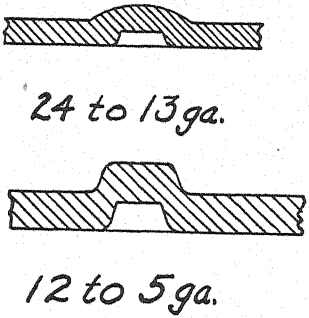


Fig. 23—Illustrating Satisfactory Forms of Projections for Different Thicknesses of Stock

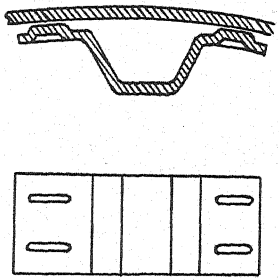


Fig. 24—Showing Elongated Projections for Curved Pieces

In the case of screw machine parts, this very often occurs in welding a stud or cylindrical piece to a flat stamping. In this case, a ring type projection is most commonly used, although the standard form of individual projections also may be used. A design of ring projection in screw machine stock is shown in Fig. 25. The ring projection may be embossed in the sheet stock (Fig. 26) and this method is often used in preference to a part formed in a screw machine, due to lesser cost of maintaining dies as compared to form tools.

Cross-wire welding is widely used in the manufacture of wire products, such as lampshade frames, soap dishes, gadgets and many forms and sizes of concrete reinforcing mesh, fence wire, etc. The general arrangement is shown in Fig. 27. It is common practice to weld any combination of sizes. Bronze, steel, coated steel (such as galvanized iron wire) and other alloys are readily welded.

A standard product using projection welding is a form of bolt or nut, in which projections are used to localize the welding current. There are many applications of this, varying from a design in which the welds are

required only to prevent the bolt or nut from jolting out of place to those in which the shear strength of the welds must equal the torsional strength of the bolt. Some designs of these nuts and bolts are illustrated in Fig. 28.

Stud welding is another form of projection welding. The stud is formed with a rounded or rounded conical end and this is held in one electrode and

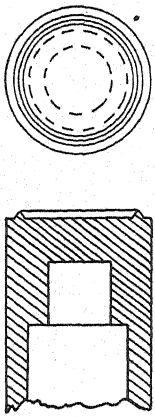


Fig. 25—Showing a Design of Ring Projection in Screw Machine Stock

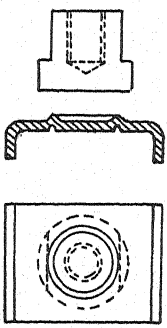


Fig. 26—Showing Embossed Ring Projection

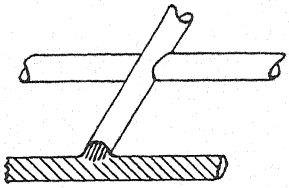


Fig. 27—Showing General Arrangement of Cross-Wire Welding

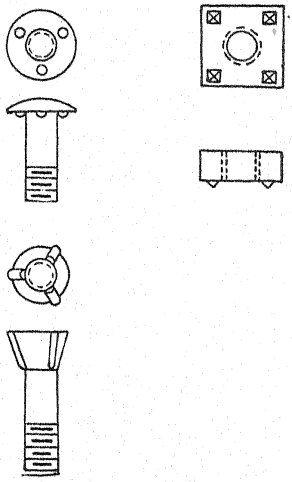
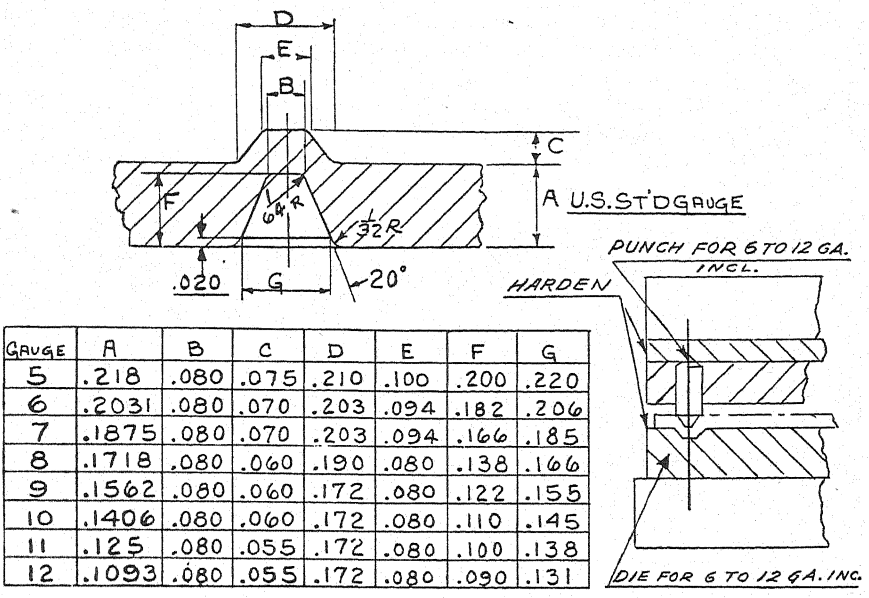


Fig. 28—Illustrating Special Bolts and Nuts Especially Designed for Projection Welding

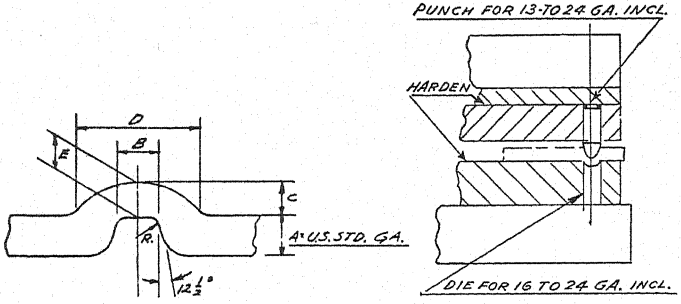
forced against a flat plate or similar surface. One application is attaching studs to steel decks for anchoring planking. It is desirable to leave a shoulder at the end to be welded, so that the electrode may bear against it. This prevents burning of the stud and provides a short current path.

There are many miscellaneous applications of projection welding. Embossments may be coined on hot or cold forgings for welding to other forgings or to sheets or stampings. Embossments may be used for locating parts for assembly and these same embossments welded to make a permanent assembly. The ingenuity of the designer has wide latitude in the application of projection welding.



GAUGE	A	B	C	D	E	F	G
5	.218	.080	.075	.210	.100	.200	.220
6	.2031	.080	.070	.203	.094	.182	.206
7	.1875	.080	.070	.203	.094	.166	.185
8	.1718	.080	.060	.190	.080	.138	.166
9	.1562	.080	.060	.172	.080	.122	.155
10	.1406	.080	.060	.172	.080	.110	.145
11	.125	.080	.055	.172	.080	.100	.138
12	.1093	.080	.055	.172	.080	.090	.131

Fig. 29—Cone Type Projections



GAUGE	A	B	C	D	E	R	GAUGE	A	B	C	D	E	R
13	.0937	.075	.050	.180	.065	1/64	19	.0437	.050	.040	.125	.035	1/64
14	.0781	.075	.050	.180	.065	1/64	20	.0375	.050	.035	.125	.035	1/64
15	.0703	.075	.045	.172	.055	1/64	21	.0344	.050	.030	.125	.030	1/64
16	.0625	.060	.045	.172	.050	1/64	22	.0312	.050	.030	.125	.030	1/64
17	.0562	.055	.040	.156	.045	1/64	23	.0281	.050	.025	.109	.025	1/64
18	.050	.050	.040	.156	.040	1/64	24	.025	.050	.025	.109	.025	1/64

Fig. 30—Button Type Projections

As outlined above, the size and shape of the projections have not been determined theoretically, but from practical data used for many years. The data given in Figs. 29 and 30 are for circular projections and data given for current and pressure requirements also are based on circular projections. The data given in Figs. 29 and 30 will serve as a guide to dimensions most commonly used, while Fig. 31 shows the range of height and diameter which has been used successfully in the welding of steel.

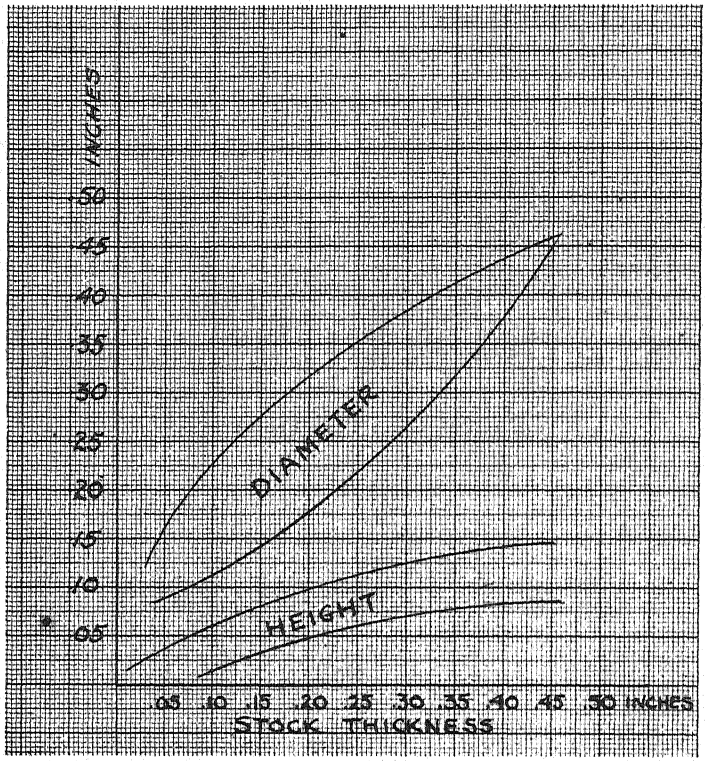


Fig. 31—Showing Range of Height and Diameter of Projections

Projections of other shapes may be interpolated in terms of the above data. It should be noted, however, that for a given thickness of stock there is an optimum height and diameter of projection. If this height is exceeded greatly, the metal at the edge of the projection is weakened and the resultant weld strength lessened. If the diameter, or area, is greatly increased, the current required is proportionately greater, but also it becomes difficult to obtain uniform current distribution throughout the weld area and the weld strength may be less than if the optimum dimensions were used.

Projection welding is usually used in multiple; that is, several projections are welded simultaneously. Therefore, the tops of all projections should be in the same plane. It is necessary that the heights of all projections be the same. If two or three projections are to be welded, a variation in height is not of such great importance, as the piece being welded

will determine a plane surface through the two or three points. However, every effort should be made to make these dimensions uniform, since variations in the height are a common source of trouble.

Projections made on screw machine parts follow the general dimensions as given above. The height of the projection is determined by the thickness of the sheet stock. It is desirable to keep the projection away from the outside edge and to allow sufficient space for the metal to flow when heated. If the projection is at the outer edge, there will be little support for the heated metal of the projection and imperfect welds may result. If the projection is adjacent to a boss, or shoulder, there will be insufficient room for the metal to flow and imperfect welds may be obtained, because the parts cannot be forced together uniformly.

Current and Pressure Required for Projection Welding

There are so many variations in projection welding, such as stock thicknesses, material, size, number and spread of the projections, also the throat area of the equipment that must be used, etc., that it is impossible to state, even approximately, the current, pressure or welding time cycle that may be adopted to a particular job.

In applying projection welding to a job, the loads or stresses to which the welded assembly is subjected, must be carefully considered. Only sufficient projections should be used (of the size above specified) to safely resist these loads. The projections are to be spaced over the maximum area available, for there is a shunting current loss when multiple projections are spaced too close. Also, the welding die life is short with projections too close to each other or too close to the limits of the die area.

Electrodes for Projection Welding

Electrodes for projection welding differ from spot-welding electrodes in that a greater portion of the electrode material contacts the work. The dies in most applications are made to fit the pieces exactly over the entire surface.

The individual plugs may be a press fit into the main die block, in which case a hole must be left in the main die for a driving pin to remove the plugs. This arrangement is shown in Fig. 32. In Fig. 33, another arrangement is shown, in which the individual dies may be removed without disturbing the main die block. Since the individual dies are held by the upper plate, different arrangements of projections may be used with the same main die block by changing only the locating plate.

Materials Which Can Be Welded

Not all metals can be welded by projections. The metal must be strong enough to support the projection. In general, brass does not lend itself to this welding method, as the projections collapse under pressure. Copper and the red brasses are considered unweldable by this method. Aluminum has been welded to a limited extent, the best results having been obtained

from extruded parts. Coated stock, such as galvanized iron, terne plate, tin plate, etc., is being successfully welded. It is also possible, in some cases, to weld dissimilar metals, such as steel to brass, steel to aluminum and steel to bronze. These latter require more current and shorter time for successful welding than is required for steel. Thin steel sheets are more readily spot welded than projection welded, due to difficulty of maintaining exact and small projections in this material.

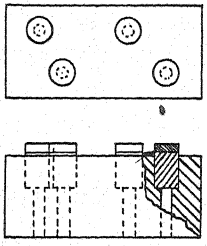


Fig. 32—Illustrating Copper Alloy Plugs Press Fit into Main Die Block for Projection Welding Dies

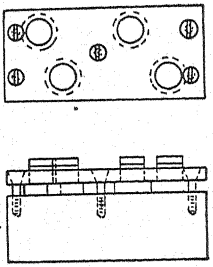


Fig. 33—Illustrating Copper Alloy Dies Held to Main Die Block by Retaining and Locating Plate

Since there are so many alloys of bronze and brass, the best solution is to cut and try, using as a starting point the data given for steel, but remembering that more current, less time and less pressure are generally required.

SEAM WELDING

General Principles of Seam Welding

Seam welding fundamentally consists of making a series of spot welds by means of one or two rotating wheel electrodes without opening the electrodes between spots. When the spots are close enough together so as to actually overlap, it is possible to make a gas- or liquid-tight joint such as a pressure vessel requires. When the spots are spaced well apart, the process is sometimes known as stitch welding. Figure 34 shows the schematic arrangement of the wheels and circuit.

By taking a section *A-A* through the welding wheels and then referring to Figs. 1 through 7 of the section on Spot Welding it will be seen that the general principles of seam welding and spot welding are the same. The individual spots made by a seam welder are of course not round as in spot welding but are rectangular or oblong depending on the contour of the welding edge of the wheel. Likewise, the spots are generally overlapping which introduces a shunting effect through the adjacent spot. This is the reason why slightly more current is required for seam welding.

Interrupters

The use of an interrupted current for most seam welding jobs is quite necessary as it gives much better control of the heat effect, allows each successive spot or weld in the seam to cool under pressure, gives less distortion

to work parts due to overheat of material adjacent to the weld, gives better control over flashes or burns caused by adverse conditions of material and makes sound welds with less surface disturbance. The choice of the correct type of interrupter is quite important. The precisely synchronous electronic interrupter is by far the best type of interrupter to be used for seam welding (for details see Chapter 11-on Controls and Timing Devices).

The use of mechanical interrupters for seam welding is not advised due to their non-synchronous switching, slow speed and other inherent inaccuracies. The only type of seam welding where an interrupter is not

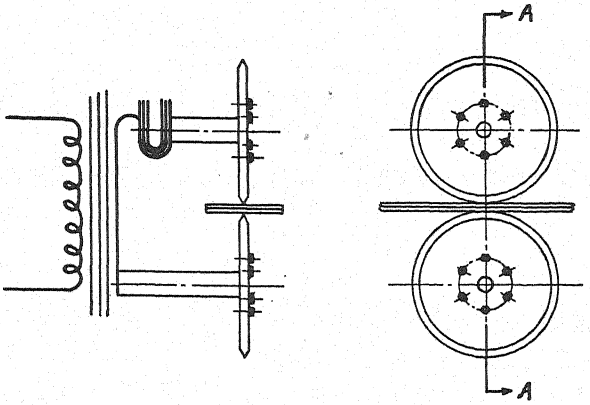


Fig. 34—Schematic Arrangement of Seam Welding Wheels and Circuit

necessary is that type of work which can be welded at high enough speeds that the frequency of the electrical circuit acts as an interrupter.

Wheel Drive

The wheel drive on seam welders may take several forms. In the so-called standard seam welding machine, the upper or lower wheel may be directly gear driven by a motor through a gear box and clutch or both wheels may be driven with the so-called knurl drive which is a steel disk or wheel formed to fit the face and a short distance up the side of the electrode wheel with the surface contacting the face of the electrode knurled to give traction. This type of drive drives both wheels at the same speed irrespective of their diameter and is particularly adaptable to the welding of coated materials such as tin plate, terne plate and galvanized iron. This type of drive tends to break up the coating of these materials picked up on the face of the electrode. In the so-called traveling roll machines, the work is clamped to a bar electrode and pushed under an idler wheel electrode, power being applied to push the work rather than to rotate the wheel. In other cases the wheel mounting member is pushed parallel to the seam

resting on the bar electrode. In the so-called multiple wheel seam welding equipment, where two wheels are connected in series across the transformer and the bar electrodes are used as shunting members under the wheels, the hydraulic drive is usually used as it gives a smoother and more constant speed motion than most types of mechanical drive.

In making several parallel seams on flat work, wheels in multiples of two may be used as there is no current interference between the various pairs of wheels on the same work piece. This arrangement of electrodes is shown on Fig. 35.

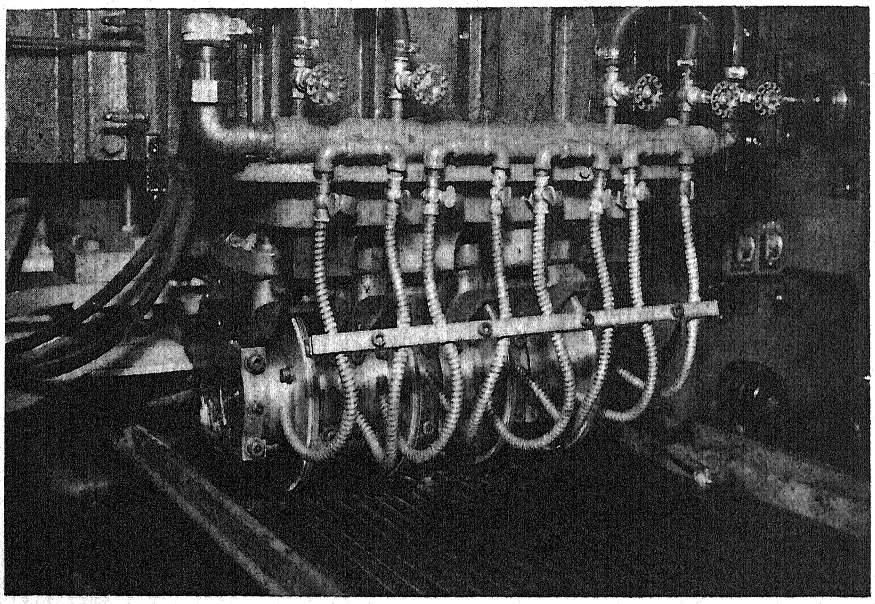


Fig. 35—Illustrating the Use of Four Wheels in Multiples of Two for Making Several Parallel Seams on Flat Work

Seam Welding Electrode Shapes and Sizes

The shape of these electrodes is shown in the sketch in Fig. 36: *A* being the shape of wheel used where clearance is available on both sides of the work; *B* where the weld must be made close to an obstruction such as a flange or the bottom of a tank type structure; *C* where an obstruction may be at right angles to a seam, a notched wheel can be used starting each time with a notch close to the obstruction and rolling away from the obstruction with the wheel. Where the obstruction is on one side only, a notched wheel and plain wheel as shown in *A* might be used. Bar electrodes may assume the face shape as shown in *A* or *B*.

The diameters may vary from a minimum of 2 in. to as much as 2 ft. for special machines. However, the common range is from about 6 to 10 in.

The usual material is a copper alloy of the heat-treated, precipitation-hardening type having properties approximating the following:

Electrical conductivity in % of copper	—75
Hardness, Rockwell B	—76
Proportional limit, psi.	—36,000
Tensile strength, psi.	—55,000
Elongation, %	—15

The edge, or face, in contact with the work commonly has a slight crown and rounded corners.

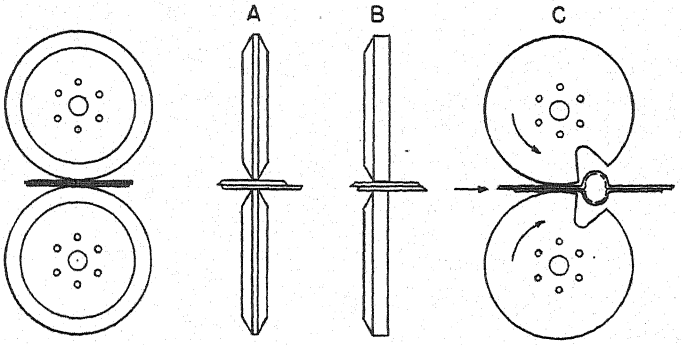


Fig. 36—Different Shapes of Seam Welding Wheels

The rate of wheel wear is determined by the pressure used, the surface condition and analysis of the material being welded, the wheel temperature as determined by values of welding current and amounts of cooling water, abrasion of work and drive rolls and the material used for wheels.

As heavier gages of steel are welded using heavier pressures and higher currents, the face widths of the wheels must of necessity be increased to avoid excessive unit pressure and excessive unit current density.

The width of the weld at a point on the center line between the two work pieces ranges from $1^1/_2$ to 3 times the thickness of one piece of the gage being welded. The higher ratio of weld width to plate thickness occurs when welding the thinner gages and this ratio decreases as the material increases in thickness. The limit of commercially practical minimum wheel face width is approximately $^1/_8$ to $^3/_{16}$ in. because of excessive wheel wear. This explains the high ratio for the thinner gages. The weld width is always slightly less than the face width when commercially practical welding schedules are used. An estimate of weld widths being 80% of wheel width is approximately correct.

Bearings for Seam Welding Electrodes

The bearings for seam welders should be designed to carry current for the full rating of the welder. The ordinary sleeve type bearing seems to be very satisfactory for most work. Roller bearings, however, are used in some cases using high conductivity bronze rollers enclosed in bronze

cages. The major portion of seam welders are constructed with the sleeve type bearing. The material in both the sleeve and shaft should be of a high conductivity material such as some of the copper base alloys used for resistance welding electrode material. One good combination of bearing and shaft is a Group A, Class 1 alloy for the shaft and a Group A, Class 3 alloy for the sleeve. Another excellent combination, but slightly more expensive, is a Group A, Class 1 shaft and Group B, Class 11 alloy inserts in a copper sleeve for the other part of the bearing. The above alloys and their classification are those given by the R.W.M.A. in their Electrode Materials. A description of these alloys will be found in Chapter 12 on Resistance Welding Electrode Materials.

In fitting these bearings for service, considerable clearance should be allowed; in the neighborhood of 0.008 in. If they are made with too close tolerances, they will seize in many cases as they start to warm up in use.

Lubrication for Seam Welder Electrode Bearings.—A high quality graphite grease such as No. $52^1/_2$ Gredag or Dixon's No. 3, castor oil or a light spindle oil should be used to lubricate seam welding electrode bearings. The graphite grease gives good lubrication and has fairly good electrical conductivity when in service. The use of ordinary greases creates considerable trouble due to their insulating the shaft and sleeve from each other electrically, particularly at rather low temperatures. The graphite grease, or above oils, however, do not give this trouble.

Welding Pressure

Because of the necessity of using current-carrying bands of standard size and weight it is difficult to keep inertia to a low figure on seam welders. In order to reduce the inertia to a minimum, a number of different pressure mediums have been used such as air, hydraulic and spring types. However, it is perhaps more important that the method of applying pressure be reliable and invariable than for the inertia to be low but the applied pressure erratic. The dynamic considerations are not as great with seam welding as with spot welding because the electrodes do not travel through any appreciable distance between individual weld impulses.

Low carbon steel is the material most widely used in industry and fortunately is one of the easiest to weld because of its wide plastic range which allows considerable latitude in the choice of welding variables.

The pressures used for seam welding are slightly higher than for spot welding with the same thickness stock. However, the unit pressure in pounds per square inch of contact area will be practically the same due to the greater area of the elongated spots made by the wheels. It will be found that a unit pressure of approximately 15,000 psi. for mild steel is a good value to use for either seam welding or spot welding. These values are based on wheel or tip contact area. Table 8 gives typical values for mild steel.

For seam welding low carbon steel, Table 8 will give the pressures used, which are satisfactory for welding these different thicknesses of material and should serve as a guide to assist in setting up seam welding jobs. The above figures hold true if the material is comparatively flat and the two

Table 8—Pressure Values and Wheel Face Widths for Seam Welding Low Carbon Steel with Interrupted Current

Sheet Thickness, In.	Welding Wheels		Wheel Pressure, Lbs.
	Diam., In.	Face Width, In.	
0.031	8	5/32	600
0.039	8	3/16	600
0.049	8	7/32	750
0.062	8	1/4	750
0.078	8	1/4	900
0.109	8	9/32	1000
0.125	8	5/16	1200

surfaces in fairly good contact with each other. If the material is deformed excessively in forming the parts, considerably more pressure may have to be used to overcome the effect of this deformation.

Table 9 gives some values for welding with continuous current.

Table 9—Pressure Values and Wheel Face Widths for Seam Welding Low Carbon Steel with Continuous Current

Sheet Thickness, In.	Welding Wheels		Wheel Pressure, Lbs.
	Diam., In.	Face Width, In.	
0.024	8	1/4	600
0.029	8	1/4	600
0.038	8	1/4	600
0.044	8	1/4	800
0.048	8	1/4	1200
0.062	8	1/4	1400

Welding Time With Interrupted Current

It cannot be said that any definite timing schedule is the best for a given stock. There are too many other variables which influence the choice such as welding speed, capacity of the machine, thickness of stock, type of joint desired, etc. Assuming a gas or liquid-tight joint is desired, the best timing will be that which will allow the fastest welding speed within the capacity of the machine. It can be said that for practical purposes and best results the time "on" should be equal to or greater than the time "off." The time "on" is determined largely by the thickness of stock while the time "off" is determined by the welding speed. That is, the thicker the stock the longer the time "on" while the faster the welding speed the shorter the time "off." Some typical values are given in Table 10.

Welding Speed—Low Carbon Steel

The welding speed, the spots per inch and the timing schedule are dependent upon each other so it is necessary to establish two of these values before the third can be determined. Inasmuch as the spot-per-inch value follows a definite relation to the thickness of stock, it can be the first to be established. Typical values are given in Table 11.

By combining these values with the timing schedules given previously it is possible to arrive at the welding speed. For example: using 0.039

Table 10—Typical Values of Current "On" and "Off" Time for Seam Welding Different Stock Thicknesses at Different Speeds

Sheet Thickness, In.	Timing Schedule, Cycles		Welding Speed, In./Min.
	On	Off	
0.031	3	3	48
	2	1	96
0.039	3	3	48
	2	1	96
0.049	4*	4	36
	2	1	72
0.062	4*	4	36
	2	2	72
0.078	6	6	24
	4*	4	48
0.109	6	6	24
	5*	4	48
0.125	6	6	24
	6*	2	48

* With one well-known seam weld timer these schedules would have to be modified slightly so that the sum of "on" and "off" times will be divisible into 60 an even number of times, i.e., 4 "on" and $3^1/_2$ "off" instead of 4 "on" and 4 "off," or 6 "on" and 4 "off" instead of 5 "on" and 4 "off."

Table 11—"Spot-per-Inch" Values for Seam Welding Different Thicknesses of Stock

Sheet Thickness, In.	Spots per Inch	Sheet Thickness, In.	Spots per Inch
0.031	12–14	0.078	10–12
0.039	12–14	0.109	9–11
0.049	12–14	0.125	8–10
0.062	11–13		

stock, the spots per inch would be approximately 13. The timing schedule might be chosen as 2 "on" and 2 "off." In order to meet these two requirements the speed would be arrived at as follows:

$$\text{Number of spots per minute } \frac{3600}{2+2} = 900$$

$$\text{Number of spots per inch } = 13$$

$$\text{Number of inches per minute } \frac{900}{13} = 69.2$$

Welding Current

The correct welding current is so dependent upon other conditions that it is not practical to try to give any rules for determining it. For example: the amount of cooling water applied to the wheels will change the current requirements. General statements might be made such as; the shorter the time "on" or the faster the welding speed the more the current required but the simple truth is that first, all the other variables must be established and then the current determined by trial and error until the desired quality

of weld is obtained. As an indication of what has been found to be successful practice, the following tabulation of data is given:

Table 12—Recommended Values for Seam Welding Low Carbon Steel

Sheet Thickness, In.	Wheel Face, In.	Speed, In./Min.	Pressure, Lb.	Time 60 Cycles On	Time 60 Cycles Off	Current, Amp.
0.032	5/32	48	600	3	3	10,800
	5/32	96	600	2	1	12,200
	1/4	120	950	2	1	13,400
0.039	3/16	48	600	3	3	12,300
	3/16	96	600	2	1	15,000
	3/16	144	600	1	1	20,200
0.049	7/32	36	750	4	4	13,000
	7/32	72	750	2	2	17,600
	7/32	108	750	2	1	19,000
0.062	3/8	19	1600	17	3	14,100
	1/4	36	750	4	4	15,400
	1/4	72	750	2	2	20,700
	1/4	108	750	2	1	21,400
0.078	1/4	24	900	6	6	15,100
	1/4	48	900	4	4	18,600
	1/4	72	900	3	1	21,300
0.094	1/4	20	1040	5	1	18,600
	3/8	17	1600	32	14	16,400
	3/8	9 1/4	980	11	9	17,000
0.109	9/32	24	1000	6	6	17,400
	9/32	48	1000	5	4	20,000
	9/32	72	1000	4	2	22,700
0.125	3/8	17	1600	39	9	17,400
	5/16	24	1200	6	6	20,800

Heat Balance

The heat balance condition as outlined in the chapter on Spot Welding will also hold true for seam welding. The condition as outlined in Fig. 12-B in the Heat Balance Section of this chapter may be obtained by using a wheel of stainless steel under some conditions. It is, however, advisable to obtain the heat balance by the other methods suggested, if possible, rather than by using a wheel of this character.

Heat Shrinkage and Weld Appearance

In making seam welds, a certain amount of shrinkage is usually experienced. This may be explained by the fact that as the weld progresses, the heated part is confined by cold metal which surrounds it in a horizontal direction and held vertically by the electrode pressure. As the material is heated it is plastically deformed and after being relieved of the electrode pressure, a slight amount of contraction takes place which, in effect, gives a shrinkage or narrowing of the weld line. The amount of this shrinkage is rather slight and will vary with different thicknesses and types of materials.

In many cases it is desirable to make seam welds with the minimum amount of marking on one side. This may be accomplished to some extent when welding with a wheel top and bottom by using a wide faced wheel on one side and a narrow faced wheel on the other. This may somewhat upset the heat balance of the weld as mentioned in a previous section but can usually be compensated for by slightly increasing the current, or in other words, running the weld slightly hotter than normal. In welding with a wheel and a bar, the side which contacts the bar will normally show less marking than the side contacted by the wheel, as in this case there is more electrode surface in contact on the bar side than on the wheel side.

Effect of Surface Condition

In seam welding, the condition of the surfaces of the material to be welded is of prime importance if quality results are required. It is very poor practice to try to weld through heavy grease, paint, scale and rust. Hot-rolled scale or annealing scale is one of the major causes of difficulty. Improper surface conditions show up as gas inclusions or scale in the fused metal. Scale causes excessive burning and marking of the contacting surfaces of the steel and of the welding electrodes. This not only causes very poor conditions on the welded surfaces but makes the welding electrode maintenance cost prohibitive. It has been found that even cleaning by steel grit blasting will create conditions where small particles of scale are driven into the surface of the steel and remain there through the welding operations. Sand should never be used for blasting to clean material for welding as enough sand may be driven into the surface to actually insulate the parts from each other and from the electrodes, or in any case, enough sand will be included to seriously affect the quality of the weld.

The most satisfactory method for cleaning is usually by pickling to remove surface scale and impurities. It is sometimes stated that it is not economical to clean material before welding but a careful study of costs will usually show that it is more economical to clean if electrode maintenance, rejects due to improper welding and the creation of an inferior product are considered in the calculations.

Cooling Fluids

In seam welding, either flood or immersion cooling is usually the best method of cooling. This is in addition to the cooling of the arms and secondary circuit of the welding transformer. Where no flood cooling is used on the work or the welding electrodes, excessive electrode maintenance and badly warped work are usually the result. In welding non-ferrous materials and stainless steel, ordinary clean tap water is satisfactory. When welding the ordinary steels which are susceptible to rusting after becoming wet, a 5% borax solution is commonly used. This borax solution may be recirculated by a small motor and pump at each machine coupled with a small sub-tank of sufficient capacity to take care of the particular welding machine. Where a number of welding machines are located in close proximity to each other, it is usually economical to install a large tank and have the welders drain or pump the solution into this tank and have a common tank for the complete installation. Whether the

single machine tank or the large tank is used, adequate water cooling coils should be inserted in the tank to keep the borax solution cool enough for satisfactory cooling of the wheels and work. The cooler this borax solution is the more efficient the cooling to be expected from its application to the wheels and work. The borax solution must not circulate through any internal piping of the machine cooling system, because plugging of these lines with borax can result.

Types of Seam Welds

There are several different types of seam welds which are commonly made at the present time. One is the lap weld where the two edges of the material are lapped sufficiently so that cool material will be left on each side of the weld itself to support the hot metal and prevent expulsion or spitting of metal which would cause a weak porous weld. Another type commonly made is known as the "series" seam weld where materials are usually lapped the full width of each piece and the welds are made with two wheels on one side connected directly across the transformer with a shunting bar on the opposite side.

Another type of weld in common use is the so-called "mash" or "butt" weld made with a seam welder. This gives a flush joint and may be used in some cases in place of a flash or butt weld. The following paragraph gives a typical procedure for making this type of weld. It is, however, not confined to this particular thickness but may be used in any thickness which can be satisfactorily seam welded. The procedure would be comparable to that used in making this joint only it would be scaled up and down to compensate for the different thicknesses in material. No interrupter was used on this particular job but the use of an interrupter might be of advantage on different types or different thicknesses of materials than the one noted.

To make a flush joint, in place of flash welding and trimming, steel 0.109 in. thick was lapped $1^1/_2$ times its thickness, tack welded to size and clamped to retain dimensions. A seam weld was made with Grade A, Class 3 rolls inside and out having faces $^3/_4$ in. wide at 72 in. per minute using no interrupter, and 3500 lb. pressure. This was a hot forging job mashing the surface down very even and suitable for vitreous enameling. Edges could be beveled for smoother joint.

Joints between a thick piece and a thin piece may be made almost as readily as joints between two pieces of like thickness. Slightly more heat may be required but the increase is not appreciable. In making joints of this type, materials with as wide a variation as 0.020 to 4 in. have been used. In some cases, when welding two sheets of very thin material, more power may be required than when welding two sheets of greater thickness due to the lower resistance to develop heat and a greater proportion of the generated heat being conducted away by the electrodes and cooling medium.

Strength of Seam Welds

No really satisfactory method for testing the strength of seam welds has been developed. However, coupons may be cut from lap welds which may be pulled in a tension testing machine. A satisfactorily made seam weld, however, usually has more strength than the parent material provid-

ing the weld itself is at least one and one-half ($1^1/_2$) times in width the thickness of the material.

Another method of testing for strength is to weld together two rectangular pieces by welding completely around these pieces near the outside and then welding on a nipple and applying hydraulic pressure and measuring the pressure applied to produce failure or bursting in the pillow thus formed. The pressure on the weld may be calculated from the area of the sample and the pressure. A properly made weld will, however, remain intact while the failure occurs in the material itself inside of the weld line. Figure 37 is an illustration of samples tested by this method.

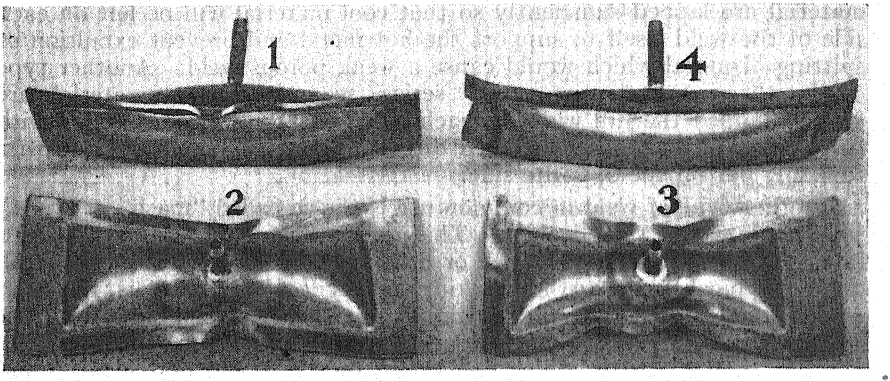


Fig. 37—Illustrating "Pillow" Method of Pressure Testing Strength of Seam Welds

Seam Welding High Carbon and Low Alloy Steels

Material of this type will usually weld satisfactorily with the exception of the quenching or hardening effect when the carbon is above approximately 0.20%. When welding steels which have a higher carbon content than the above, usually some subsequent heat treatment must be used to remove the excessive hard and brittle zone in and near the weld. It is not possible to weld high carbon materials without this hardening effect as the material is raised appreciably above its critical point and then quenched by heat being conducted away through the electrode and cooling medium in a very short time.

The low alloy steels, in some cases, may be welded satisfactorily without subsequent heat treatment depending largely on the particular type of steel in consideration and its carbon content. Each application should be studied from a metallurgical standpoint to determine whether or not it may be welded satisfactorily without subsequent heat treatment or if it must be heat treated to establish the proper physical properties. It sometimes is of help in welding these steels to use longer time and lower energy input with slower wheel travel so that the quenching effect is not so drastic as it is with the higher speeds. No information is available on the exact procedure used in these various alloys but as a start for working out the welding procedure, the procedure used for low carbon steels may be used and modified to suit the conditions of the particular material being investigated.

Seam Welding Plated and Coated Steels

Most of the plated and coated steels may be satisfactorily welded, the procedure not being greatly different from that used on the uncoated steels of similar composition. However, materials like terne plate, tin plate and galvanized iron usually require slightly higher pressures and currents than material without the coating.

The welding of these materials with the low melting point coatings gives some difficulty in that the coatings alloy with the wheel surfaces and the wheels have to be cleaned frequently. The use of knurl drive on the seam welders used for welding coated materials helps to break up the alloy coating and pickup on the wheel faces making the cleaning periods less frequent.

The welding of nickel plated steel is not appreciably difficult although it does destroy the nickel plating to some extent over the weld area. When welding the chrome plated materials, the chrome is also usually destroyed in the weld area while with materials like tin, zinc and lead, while the coating invariably melts, there is usually enough left in the weld area to give at least partial protection against corrosion.

There are no welding procedure charts available for the welding of these plated materials. Little difficulty, however, should be experienced in welding them if the procedures used in welding mild uncoated steels are used as a basis for set-up and modified by usually increasing pressures and currents, and sometimes using slightly lower wheel speeds to compensate for the coating on the materials.

Seam Welding High Alloy Steels

Refer to Chapter 20 for general principles of welding.

The stainless steels, particularly of the so-called 18–8 type weld very readily. They should be welded in short time to prevent carbide precipitation as mentioned in the spot-welding chapter.

Table 13 gives procedure for welding a few combinations of 18–8. Very little actual data are available on welding these steels.

Table 13—Procedure for Seam Welding a Few Combinations of 18–8 Stainless Steel

Sheet Thickness, In.	Wheel Face, In.	Speed, In./Min.	Pressure, Lb.	Current, Amp.	Time Cycles On	Time Cycles Off
0.005	1/8	30	650	12,500	1	5
0.020	1/8	30	900	8,640	2	3
0.025	3/16	72	750	6,300	2	2
0.035	3/16	60	1000	7,500	2	4
0.049	1/4	36	1150	8,600	3	7
0.062	3/8	30	1400	9,500	3	9

Seam Welding Copper and Copper Alloys

The seam welding of copper is nearly impossible due to its high conductivity and low plastic range; however, many of the copper alloys weld

quite well. They require higher current, slower wheel speed and, in general, lower pressures than low carbon steel.

Reference to an earlier section of this chapter on the spot welding of Copper and Copper Alloys will give further data on the weldability of these materials.

Seam Welding Nickel and Nickel Alloys

Refer to Chapter 24 for general information on weldability of these alloys.

Nickel and its alloys, like Monel and inconel, may be seam welded but no definite procedure is available.

Seam Welding Aluminum and Aluminum Alloys

Due to the narrow plastic range of aluminum and its alloys compared to steel, it is necessary in seam welding to use a shorter time "on," slower speed and more spots per inch than with steel. More current is required because of the higher electrical and thermal conductivity. For details on this subject see Chapter 23.

Seam Welding Magnesium Alloys

Magnesium is weldable as are most of its alloys (see Spot Welding Magnesium Alloys) but very little is known about it's seam welding properties and no data are available.

Work Limitation

The design of parts usually limits what can be successfully seam welded. When designing parts, a study must be made of the equipment available, and the product designed so that the seams will be accessible to the welding machines that are now designed or can be designed for a given product. Material in thickness from 0.003 in. or 0.005 in. to about 0.187 in. can be welded by standard equipment and mild steel up to two pieces of $^3/_8$ in. has been welded with special equipment.

Welding Dissimilar Metals

Generally most metals or alloys that will alloy together and form a useful alloy may be seam welded.

When planning to weld a dissimilar metal combination, careful study should be made from a metallurgical standpoint to see if a weld can be expected. As an example, we know that an alloy of copper and aluminum would be brittle so we should not expect a strong ductile seam weld between them. On the other hand, we know that iron and nickel will form a ductile alloy so we should expect that iron and nickel would weld satisfactorily to each other.

In welding dissimilar metals we must also take into consideration the heat balance factor as described in the spot-welding chapter.

Taking into account the above factors, it is possible to seam weld in dissimilar combination a major portion of the metals and alloys.

Production Speeds

In determining production speeds, a number of factors must be taken into consideration, including physical size and shape of parts, handling facilities, type and capacity of welding equipment, gage and kind of material, quality of product, whether a pressure-tight or strength weld is required, power available, quality of equipment, maintenance and production required. With optimum conditions, speeds of 10 in. to 60 ft. per minute are possible, depending on the type of product expected and the factors outlined above.

Metallurgy of Seam Welding

Metallurgy plays an important part in all welding. Before attempting to weld any metal or combination of metals, they should be carefully studied from a metallurgical standpoint to determine what to expect in the weld zone from the high temperatures reached in welding, and what the effect of the rapid cooling from these high temperatures will do to the physical properties.

For example short weld time will prevent carbide precipitation as in 18–8 stainless steel. Or, in the case of high carbon steel, subsequent heat treatment may be required.

If we are to expect a first quality product from our welding equipment, we must control all the factors involved: metallurgical, mechanical and electrical.

FLASH AND UPSET BUTT WELDING

Definitions

Upset butt welding in its simplest form consists of placing two pieces of metal together, in contact, so that their juncture forms the place of highest resistence in an electric circuit, and the passing of an electric current of sufficient magnitude through this juncture to produce heating and fusion at the juncture, with the weld being consummated by the application of sufficient pressure. Figure 38 shows the elements of this application.

Flash welding consists of placing two pieces of metal in an electric circuit adjacent to each other, in very light contact (or with a minute air gap between them) and the passing of an electric current of sufficient potential and magnitude through the circuit to form a "Flashing" action between the adjacent pieces of metal, thereby heating them to the fusion point with the weld being consummated by the application of sufficient pressure. Figure 39 shows the relationship of parts for this application.

General Principles of Upset Butt and Flash Welding

In upset butt welding the heat for welding is generated mainly by the contact resistance between the two pieces and is expressed by Ohm's law.

The unit contact resistance is a function of the surface resistivity of the pieces, the nature of the surface and the unit pressure between the two surfaces and is approximately inversely proportional to the unit contact pressure.

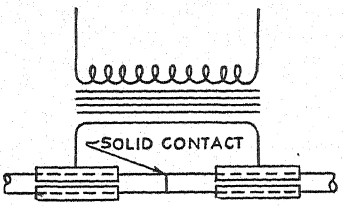


Fig. 38—Elements of Upset Butt Welding

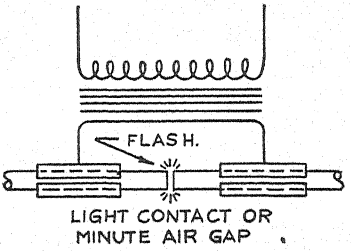


Fig. 39—Relationship of Parts for Flash Welding

In practice the pressure and current persist during the entire weld, and the pressure is usually started at a low value (just enough to prevent arcing between the pieces) and is increased to such a value as will give the necessary forging squeeze when the fusion point has been reached. After the work has upset the desired amount the welding current is cut off and the pressure is removed.

In upset butt welding of large areas of pieces that do not make good contact with each other, the welding current is interrupted periodically to allow heat to flow into colder portions of the work so as to prevent localized overheating and melting.

Upset butt welds are generally characterized by large symmetrical upsets.

In a flash weld the heat is generated by the "Flashing" action.

It is generally assumed that the flashing generates heat in three different ways.

First, there is a very light localized contact between the two abutting surfaces. This results in extreme localization of heat in the minute area in contact and the material in this area is raised to the melting point and is blown out in the form of incandescent particles. Second, as soon as a particle is blown out a minute arc is formed which persists until it is quenched by the metal in this area again touching, or it may be quenched by the magnetic blow-out effect of the transformer core. These minute contacts occur successively over the entire surfaces and at an accelerating rate until the entire surfaces are at the fusion temperature. Third, also there is a certain amount of heat generated by the combustion of the molten particles as they are thrown out by the flashing action.

As soon as the fusion temperature is reached the upset or forging pressure is applied suddenly and the welding current is cut off to complete the weld.

The flashing action during the heating period also probably helps to protect the weld while it is being made due to the combustion of the incandescent particles and the expulsion of these particles together with entrapped gases.

Flash welds are characterized by comparatively small upsets and a ragged line of extruded "flash," which is greater on the side of the piece that is turned away from the welding transformer during the weld.

Fields of Application

Upset butt and flash welds are most commonly employed in joining two pieces of metal end to end or in welding one piece of metal to a projecting part of another piece. Common examples of these types of welding are the welding of strips end to end in steel making and processing to form a continuous strip, the welding of circled strips or bars to form rings (as in automobile wheel rims, ring gears, etc.) and the welding of tubular sections end to end (such as safe ending locomotive flues).

While in general either upset butt or flash welding may be optional on most jobs, the upset butt weld has generally fallen into disuse (except in the small wireworking industries) and has been supplanted by flash welding because of the following advantages of the flash weld:

1. Greater weld strength.
2. Special preparation or machining of weld surfaces not required.
3. Smaller power demand.
4. Less power consumption.
5. Greater speed.
6. Smaller upset.
7. Less heat developed in body of work.
8. Generation of heat occurs largely at the welding surfaces.
9. Dissimilar metals varying widely in individual fusing temperatures may be welded because flashing may be carried on until both metals have reached their own individual fusing temperature.

The disadvantages of the upset butt weld are:

1. Less weld strength.
2. Necessity of machining or preparing weld surfaces.
3. Larger upset.
4. Longer welding time.
5. Body of work heats more.
6. Greater power demand and consumption.

However, for certain types of work where flash spatter and ragged flash extrusion are objectionable and the removal of these is not practical the upset butt weld possesses the following advantages:

1. No flash spatter.
2. Very little ragged extrusion.
3. Upset usually smooth and symmetrical.

In some cases the flash weld has the following disadvantages:

1. Larger amount of flash spatter.
2. Ragged flash extrusion.
3. Sometimes difficult to remove flash extrusion (usually only on high carbon or air hardening steels).

Sometimes where a large symmetrical upset is desired, an upset butt weld will accomplish this better than a flash weld.

There are no inherent technical difficulties encountered in the development of large butt and flash welders and at present the main limiting factor controlling the capacities of these machines is power supply with the factor of difficulties of construction, a secondary consideration.

Due to the greater development of flash welding and the relatively smaller power demand, practically all units above 300 kva. capacity are flash welders.

The largest electrical rating of a machine built to date is 10,000 kva. and the greatest welding capacity is approximately 500 sq. in. Several welders are in use producing flash-welded pipe where the weld is 40 ft. long in metal approximately 1 in. thick.

Undoubtedly, the size of these units will be exceeded if it is economically justified.

Preparation of Work

Ordinarily in industrial practice no special preparation of the surfaces of the work for electrode contact is required on rolled stock or on stampings or on grit-blasted forgings.

Where there are heavy coats of mill scale (butt-welded black pipe for instance), or forging scale or heavy deposits of rust or slushing grease, these coatings must be removed by grit blasting, belt sanding or some other suitable method.

Rust, scale and grease are insulators, or very poor conductors, and when an attempt is made to carry welding current through them, they break down in spots only and the resulting localization of current causes over heating and arcing between the work and the electrode surfaces.

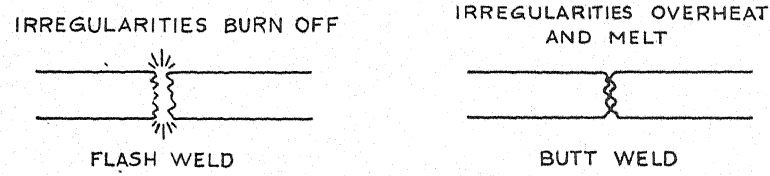


Fig. 40—Illustrating Necessity for Relatively Smooth and Parallel Surfaces for Butt Welding as Contrasted with Flash Welding



Fig. 41—Showing Result of Poor Alignment in Flash or Butt Welding

On badly pitted and rusted work, such as reclaimed pipe and boiler flues belt sanding is necessary.

In general, rough, irregular or haphazard contact surfaces are unsatisfactory as they result in poor work alignment, rapid electrode wear, burned spots on work and poor welds due to irregularities of resistance and consequent variations in welding currents.

For flash welding no special preparation of the weld surfaces is required as irregularities are burned off during the flashing period and any foreign matter is expelled with the flash.

For upset butt welding it is usually necessary to machine the weld surfaces on rolled stock, forgings and castings. Stampings are usually trimmed in a die but are sometimes machined.

In making upset butt welds the welding surfaces must be clean and parallel and comparatively smooth for otherwise the high spots will overheat and melt before the areas that are not in contact begin to heat. This is shown in Fig. 40.

Aside from the alignment requirements of any particular job the two pieces of work should be in alignment to within about 10% of their thickness to prevent "slip over" at the upset, as shown in Fig. 41.

This is particularly true of work less than $1/2$ in. thick.

Metal Allowances for Flash Welding

In making a flash weld an allowance in stock length has to be made for "burn-off and push-up." The burn-off represents metal that is expelled from the weld as flash during the heating period and the metal used in the push-up goes to close up all irregularities of the weld surface or is extruded to the outer surfaces of the weld.

The total allowance is from one to six times the stock thickness and decreases as the stock thickness increases.

The push-up allowance, out of the total metal allowance for making the weld, varies with the flashing voltage used but is usually one-fourth to one-third of the total allowance. The higher the flashing voltage, the greater the push-up allowance must be.

Table 14 shows average practices for weld allowances when using hydraulically or cam operated welders.

Table 14—Average Practices for Total Weld Allowances (for Steel) Using Hydraulically or Cam Operated Flash Welders

Stock thickness, in.	1/16	3/32	1/8	3/16	1/4	3/8	1/2	3/4	1	1 1/2	2	4
Allowance, in.	3/8	7/16	9/16	3/4	7/8	1	1 1/4	1 3/8	1 5/8	2	2	2 1/2
Round stock, in.	1/16	3/32	1/8	3/16	1/4	3/8	1/2	3/4	1	1 1/2	2	4
Allowance, in.	1/8	3/16	1/4	5/16	3/8	7/16	1/2	3/4	7/8	1 1/4	1 5/8	2

In welding on a hand-operated machine the allowances shown in Table 14 are decreased 25 to 50%.

Electrodes

Electrode shape is mainly dependent upon the parts to be welded, and the

size of the electrode is dependent on the size of the work and the necessity of mechanical rigidity to resist deflections from thrusts resultant from the upset pressure, so as to maintain proper alignment of work.

As much electrode contact area, as is practical, should be provided, and where it is practical the contact surfaces should be made as small inserts in the body of the electrode to reduce cost of replacement.

The minimum practical contact area for electrodes, from the electrical standpoint only, is about one and one-half times the weld area and the desirable contact area is five to six times the weld area.

Small contact areas require excessive clamping pressures and consequently have a short life and high maintenance cost and are one of the most prolific sources of trouble in flash welding.

Excessively large contact areas are also likely to prove unsatisfactory, as the large area reduces the available pressure per unit area, and results in erratic contact due to slight irregularities on the work.

Both soft and hardened steel electrodes have been used successfully for flash welding relatively small sections where large contact areas are available, but for general use they are impractical. One of the main objections to steel electrodes is that flash spatter welds to them.

For detailed information on available electrode materials see Chapter 12.

Clamping Pressures

Whenever practical the two pieces of work are "backed up." That is they are placed so that their outer ends bear against fixed stops on the platens of the welder, and the upset pressure is transmitted to the work by these fixed stops. In this case the clamping pressure on the electrodes has only to be sufficient to provide a low resistance path for the welding current and to maintain alignment of the work.

For "backed up" work the usual range of clamping pressure is from 3000 to 4500 psi. of weld area (not electrode contact area).

Where it is not practical to back up the work (such as circular rings or long pipes, etc.) the clamps have to grip the work with sufficient force to prevent slippage of the work when the upset pressure is applied. This pressure is far greater than that required for good contact and alignment purposes and is governed by:

1. Amount of upset pressure.
2. Material being welded.
3. Character of surface of this material.
4. Material in gripping electrodes and jaws.
5. Coefficient of friction between welded parts and electrodes and jaws.
6. Areas in contact.
7. Unit clamping pressure.

As the coefficient of friction varies with the nature of the contacting materials, the character of the surfaces in contact, the hardness of the surfaces and the unit pressure, it is difficult to establish even an empirical formula for necessary pressures to prevent slipping.

It has been a common practice of welding machine designers to assume a ratio of $2^1/_2$ to 3 times the upset pressure for determining clamping pres-

sures and this is probably on the safe side with unit pressures of above 3000 psi., when welding steel, as results have proved satisfactory in most cases.

The seizing point of rolled steel surfaces on copper or bronze electrodes (up to 150 Brinell) averages about 4500 psi., so that it is probable that in most cases the clamping pressure is just about at the seizing point.

Where one of the clamping jaws is made of steel and slight marking of the work is not objectionable, this clamping jaw is made with teeth or serrations so as to reduce its contact area and increase the unit pressure above the seizing point.

When welding circular rings of heavy cross-section considerable pressure is required (depending on relationship of diameter to cross-section) to close these rings up in addition to the pressure required for the upset. In this case the clamps must supply sufficient pressure to prevent slippage against the resistance of the work to bending as well as against the upset pressure.

Clamping pressures for stainless steel must be about 40 to 50% higher for contact purposes than on other materials, as the stainless steels are covered by a thin, high-resistance film of chromium oxide, and unless sufficient clamping pressure is employed there is a tendency for current to break through this film in spots and cause arcing between the work and the electrodes.

Upset Pressures

Upset or forging pressure is expressed in psi. of weld area. For upset butt welds this pressure varies from 2500 to 8000 psi., and for flash welds from 5000 to 25,000 psi, depending on the alloy welded.

In flash welding, sufficient pressure must be applied to close up all voids in the weld area and to extrude all metal in the molten or semi-molten state along with slag or other impurities.

As the weld area becomes more compact (approaches a circular section) the upset pressure required per sq. in. increases, due to increased resistance to extrusion in more concentrated areas.

Welds made with insufficient pressure are characterized by porosity, inclusions, low strength and poor impact resistance.

Excessive upset pressures will produce poor welds also as all of the metal in the plastic welding range may be forced out by the excessive pressure. Where excessive pressure has been used the weld usually shows satisfactory tensile strength but has poor impact and fatigue resistance.

Table 15 shows ranges of upset pressures now being used in average practice.

Speed of the upset is a very important factor in making satisfactory welds. While the flashing action is going on the weld is protected from contamination but as soon as the upset starts the flashing action ceases, and any time interval between the cessation of the flashing action and the consummation of the upset allows oxidation of the high temperature weld surfaces to begin.

Speed of upset cannot be overemphasized because many poor welds may

Table 15—Range of Flash and Butt Welding Upset Pressures Used in Average Practice

Material	Thickness (In.)	Pressure Range (Psi.)
Aluminum	Up to 5/8	4,500 to 5,500
Copper	Up to 3/4	5,000 to 7,500
1020 steel	Up to 3/8	6,000 to 8,000
1020 steel	Up to 1	7,000 to 10,000
1020 steel	Up to 2	9,000 to 11,000
1020 steel	Up to 4	10,000 to 12,000
2340 3140 steel	Up to 1	10,000 to 12,000
4140 6145 steel	Up to 1 1/4	11,000 to 18,000
Stainless	Up to 2	13,000 to 25,000

be traced to slow upset speed, even though all other welding conditions are satisfactory.

Welding Currents, Voltages, and Speeds

Currents ranging from 2000 to 5000 amp. per square inch are used for slow butt welding of steel. Few data are available on current requirements for butt welding other material.

In making flash welds in steel currents range from 2000 to 25,000 amp. per square inch during the flashing period, and from 2000 to 50,000 amp. during the upset.

The current is adjusted to the proper value required for the flashing action and the value that it rises to during the upset period is a function of the regulation of the welding transformer, and although the exact relationship between current during the upset and quality of the weld has not been definitely established, experience seems to indicate that it has very little bearing and is not at all critical.

However, this should not be taken as a license to design flash welding transformers with wide regulation in an effort to reduce peak power demand, as due to inherent design characteristics, the normal regulation is very wide and any greater regulation causes erratic and unstable flashing.

The selection of the proper flashing current depends on the time to be consumed in making the weld.

The low limit is the lowest value at which a stable flash may be maintained and is about 2000 amp. per square inch regardless of metal thickness (on very small welders this value is probably around 3000 amp.).

The upper limit is determined by the material being welded and the stock thickness. Above 1/8-in. thickness as stock thickness increases relatively lower current values must be used due to the necessity for slower heating to allow heat to run back from the weld faces to secure a wider zone of plastic metal necessary for a proper upset.

Table 16 shows some welding currents and flashing speeds that have been used for steel.

In welding circular rings (such as wheel rims) or other closed shapes where the diameter is large (above 50 times) in relation to the metal

Table 16—Welding Currents (Amps./Sq. In.) and Flashing Speeds for Steel

Thickness	Min. Current (Amp.)	Max. Current (Amp.)	Max. Time (Sec.)	Min. Time (Sec.)
18 gage	2000	6,500	7	3.2
1/16 in.	2000	7,500	9	3
3/32 in.	2000	10,500	9	2.5
1/8 in.	2600	25,000	10	1.1
5/32 in.	2600	23,500	10	1.6
3/16 in.	2600	22,000	12	2.3
1/4 in.	2800	20,000	18	4.7
3/8 in.	3000	18,000	24	8
1/2 in.	3000	18,000	26	11
3/4 in.	3500	17,000	60	25
1 in.	3500	17,000	90	40
2 in.	..	17,000	..	65

thickness, about 25% more current must be allowed for back leakage As the diameter to metal thickness decreases, on rings, the allowance for back leakage must be increased. Where this ratio is very low (as in chain links) the back leakage is so great that a flash cannot be maintained between the ends and an upset butt weld must be resorted to.

Voltages employed in upset butt welding vary from 1/2 volt to 5 volts and from 3/4 volt to 20 volts for flash welding, depending upon the size of machine employed and the design of the secondary loop.

Table 17 shows open circuit secondary voltage ranges commonly used for various sizes of flash welders.

Table 17—Open Circuit Secondary Voltage Range Commonly Used for Various Sizes of Flash Welders

Size of Machine	From	To
10 kva.	0.75	2.5
25	1.25	3.5
50	2.0	5.0
100	3.0	7.0
300	4.0	8.5
500	6.0	11.5
1000	8.0	13.0
2000	10.0	20.0

These are open circuit secondary voltages and the actual flashing voltage at the weld is from 1 to 2 1/2 volts lower than these values due to resistance and reactance voltage drops in the secondary loop.

The lowest flashing voltage possible for the desired flashing speed should be employed, for as the voltage, and consequently the current increases, the size of the flash particles thrown out increases, thereby leaving greater irregularities on the weld surface to be closed up by the upset.

Flash welding transformers are usually built with tapped and extended primary winding to provide either six or eight steps of adjustment. Where a wide variation of work must be welded on the same machine (job shop or tool shop work, etc.), an autotransformer must be used to provide a greater range of adjustment than is practical to secure with the tapped primary of the welding transformer.

As the adjustment provided by the voltage steps of the welding transformer is relatively coarse, finer adjustments are made by varying the flashing speed.

On hand operated machines the operator simply moves the operating lever slower or faster. Hydraulically operated machines are usually provided with variable feed valves and cam operated machines are generally built with variable-speed transmission for speed variation.

The movement of the parts together as flashing proceeds may be at a constant speed or at a variable accelerated speed.

On hydraulically operated machines constant speed is generally employed, but sometimes these machines have two speeds, the lower speed being used to start the flashing action and the change being made to the higher speed when one-half to two-thirds of the metal to be flashed off has been removed.

On slow speed cam operated flash welders both constant and accelerated speeds are used.

On high speed cam operated flash welders it is necessary to use an accelerated motion for a constant motion results in too high speed at the beginning of the weld (difficulty in starting flashing action) and too low speed at the finish of the weld (difficulty in closing up voids in weld area because flash particles become coarser as flashing progresses unless speed is increased).

Flash welding cams are usually laid out with uniform acceleration.

Sequence of Operation

In making a flash weld the following sequence of operation is followed

1. Load machine.
2. Clamp.
3. Welding current applied.
4. Parts brought into light contact (to establish flash).
5. Flashing.
6. Upset.
7. Welding current discontinued.
8. Unclamp.
9. Unload.
10. Return platen.

While there has been some tendency in practice to discontinue the welding current just before the upset occurs, so as to reduce the "bump" on the power system this is poor practice, for there is always a time interval involved in making the upset and the weld is not protected by the flashing action during this interval. This results in many weld failures for which it is often hard to assign any cause.

For the majority of purposes the welding current should be discontinued just as all voids are closed up and a solid upset is secured. However, delayed current cut-off does no harm if not delayed too long and only causes a slightly larger upset.

In some cases a light upset is first applied to the work (just enough to

stop flashing), the welding current is kept on for an interval and then a second, heavier, finishing upset is applied. This is usually done when welding truck rim sections made of rolled, killed steel.

Heat Balance

In flash welding dissimilar metals or dissimilar sections where the electrical resistance of the two pieces is very much different, some method of balancing the heat in the two pieces must be resorted to so as to prevent the piece with the higher resistance from overheating.

This is accomplished by projecting the lower resistance piece farther from the clamping electrodes so that its length of resistance path is increased. This unequal projection of the work throws the weld off center in the electrode space, toward the electrode holding the higher resistance piece, and this also helps to equalize the heat. The electrodes remove large amounts of heat from the work and as the electrodes are nearer to the weld on the high resistance side more heat is removed from this side.

The proper projection for each piece of work has to be determined experimentally and is a relatively simple matter.

Preheating and After Treatment of Welds

Preheating is not necessary ordinarily in making flash welds, but is resorted to when welding sections that are larger than the flash welder is normally intended to handle. Preheating is sometimes used on large compact sections that are hard to get the flash started on.

When welding high carbon tool steel and tungsten high-speed steel preheating is generally used to reduce internal stresses which would be set up in the weld by the quenching action of the body of metal back of the weld, if cold parts were welded. Sometimes when preheating is not used parts will crack before they can be removed from the welder.

Welds in steel with 0.40 carbon or below are seldom given any heat treatment and steels between 0.40 carbon and 0.50 carbon are generally stress relieved or annealed and this procedure is absolutely necessary on steels of above 0.50 carbon.

When flash welding the austenitic stainless steels there is a section of the work on either side of the weld and somewhere between the weld and the face of the clamping electrodes that is in the chromium carbide precipitation range (900 to 1500°F.). Also, as the weld area cools it passes through this carbide precipitation range and the amount of carbide precipitation depends upon the cooling rate. Therefore, it is necessary to anneal these types of steel. This is accomplished by heating to about 1900 to 2100°F. and quenching in water. The steel manufacturers should be consulted as to the best procedure.

Flash Trimming

Removal of the extruded flash and part of the upset metal and in some cases all of the upset metal is necessary on some work and is accomplished by one of the following methods:

1. Air chisel.
2. Machine tool metal cutting tools.
3. Grinding wheels.
4. High-speed burring wheels.
5. Die trimming.
6. Cutting torch.

The air chisel is employed on inside or other surfaces that are otherwise inaccessible.

Metal cutting tools fall into five general classes for flash removal:

1. Draw cut shaper type (for flat stock).
2. Fish tail type (for flat stock).
3. Lathe type (for circular work).
4. Rotary milling cutter type (for flat and formed sections).
5. Oscillating knife type (for flat and formed sections).

Grinding and high-speed burring wheels are usually used on small parts. Grinding wheels are also used where the flash hardness is too great for cutting tool removal.

Die trimming is usually used on stampings where the upset is relatively light.

The cutting torch is used on very heavy work where there is a large amount of metal to remove.

Metals That Can Be Flash Welded

Because nearly all the common metals and their alloys in common commercial use have been successfully flash welded it is easier to give the metals that have not been successfully flash welded, rather than to give the list that has been welded.

Lead, tin, zinc, antimony, bismuth, and alloys in which they are the principal constituents, and copper alloys in which any of the above metals are present in large percentages have never been successfully flash welded.

Cast iron has been flash welded but is not practical from a commercial standpoint.

All types of steel have been welded to their own type and to all other types, and to practically all other metals and alloys with the exceptions noted above.

With these exceptions, flash welding can be considered applicable to all combinations of metals, regardless of their dissimilarity, although all conceivable combinations might not be practical for ordinary commercial uses.

Summary

In the past twenty years flash welding has become one of the most valuable and widely used production processes and its use will still further increase because of its many advantages:

1. Reliability.
2. Speed.
3. Low cost.

4. Widely dissimilar metals and sections may be welded.
5. Little operator skill required.
6. Ruggedness and simplicity of equipment.
7. Cost savings due to design advantages.
8. Many designs would not be practical without it.

SPECIAL PROCESSES OR TECHNIQUES

General

Although the number of special resistance welding processes is very great because of the great flexibility of the process, there are several special resistance welding processes, the use of which is sufficiently wide to justify brief description.

These processes are as follows:

1. Pulsation Welding.
2. Percussive Welding.
3. Stored Energy Welding.
4. Electro-Brazing.

It is the purpose of this Section to give a brief description of these processes as well as their common application.

Pulsation Welding

Definition.—Pulsation welding is defined as a spot or projection welding process wherein the welding current is interrupted one or more times without release of pressure or change of location of electrodes. In other words, it is a process wherein the welding current "or heat" is applied repeatedly for the making of a single weld, or simultaneous welds, in parts clamped between electrodes at rest when a single like impulse of the same current is not sufficient to produce the desired weld.

It has occasionally been the practice for resistance welding operators to "nurse the welding heat along" by manually interrupting the flow of welding current during certain welding operations. Such a practice is, of course, erratic since it depends on the judgment of the operator and his ability to duplicate the procedure on successive welds. Through automatic controls and identical series of current applications during one automatic machine operation pulsation welding is possible and has many applications.

Advantages.—Pulsation welding as applied to production jobs is being recognized as an increasingly important process. The advantages which are more evident on jobs involving thicker material are:

1. Increased electrode life.
2. Thicker material can be welded in production than was practical before.
3. Thicker material can be welded with the same equipment.
4. Better welds are produced in many cases.
5. Any tendency of the weld metal to "spit" or "splash" is noticeably reduced by interrupting the current flow.

6. A multiplicity of thin sections, stacked to a greater height, may be spot welded together.

Pulsation welding is used to advantage not only in spot welding but also in seam welding, butt welding and projection welding. When seam welding by this method, the usual rolls or "wheels" may be intermittently driven by Geneva motion or other well-known methods to allow repeated impulses of welding current to make each of the individual welds. This is pulsation roll-step seam welding. Steel plates $^3/_8$ in. thick have been thus seam welded together. By pulsation butt welding, costly finished machine parts have been production welded, eliminating flash and loose particles with consequent cleaning operations, yet maintaining close tolerance as to over-all length of finished welded dimensions without sacrifice of strength. Pulsation projection welding has made a success out of many jobs which otherwise were failures, because of the more favorable rate or method of heating. This is particularly true where several projection welds are made simultaneously. The several projections seldom contact uniformly and a single impulse of power often blows some projections away before the others make good contact. By properly interrupting the flow of current, the first projections may be upset instead of being burned off and 100% strength obtained.

Job 2 in Table 19 illustrates this point. The bracket ties the two ends of the ring together and dependable strength is required. No welding process proved satisfactory in both strength and cost until pulsation projection welding was applied. Previously the eight projections seldom welded alike.

Theory.—These benefits result from at least two distinct actions:

1. In multiple projection welding or with large annular projections in heavy parts, appreciable heat must be developed to bring both surfaces to the welding temperature. A smaller current applied for a longer total time produces heat but results in poorer distribution between projections or around the circle. Pulsation welding uses a larger current to force a better distribution, but interrupts it before hot metal is blown out. After this heat has spread, another like impulse of current is applied to bring the temperature up a little higher. These impulses are repeated until the welding temperature is developed.

2. The water cooling of the electrodes is much more effective. The temperature of water-cooled electrode tips may be greatly reduced while the flow of current is interrupted, yet, while welding thick parts, the temperature at the weld point will be only slightly influenced by the water cooling in the short time. This has greatly extended the life of electrodes on heavy work and has made the spot welding of heavy parts such as 1 to 1 in. and $^1/_2$ to $2^1/_2$ in. practical.

It is apparent that it is necessary for a spot or projection welding machine to maintain pressure for an extended length of time for some pulsation welding jobs. If a motor operated machine will not run slow enough, the motor may be stopped with the head in the down position to make the weld. Motor operated machines are available, arranged so that the clutch will disengage with the head in the down position as well as with the head up. Air and hydraulically operated machines are easily converted to give any desired delay for pulsation welding.

Just as the water cooling of electrodes is more effective with pulsation

welding, so is water cooling of the transformer. By this method larger jobs can often be welded by a given machine. As a correlation, when the electrode surface is saved, the surface of the material is saved. Pulsation welding is thus of advantage when spot welding near the edge of a piece or in spot welding a narrow strip to another surface. When the surface in contact with the electrode is kept more solid, there is less deformation.

The over-all time for pulsation welding may be greater than when using a single application of heat; however, as a general rule, the welding time is so short compared with loading and unloading time, that the same time studies can usually be used as with single heat application when pulsation welding is used.

Practice.—As to adjustments, pulsation welding has almost unlimited values to choose from for any particular job. The adjustment of the number of interruptions and the duration of the "on" and "off" times will produce a wide variation of results while using identical transformer and pressure adjustments. Usually the length of power impulse and the "off" periods are constant, like using a certain number of impulses from a seam welder control. However, automatic controls are available which will deliver varying values of which the following is an example:

The sequence for a certain butt-welding job, using 60-cycle power, was set up with 5 cycles on, 5 cycles off; 10 cycles on, 5 cycles off; 15 cycles on, 5 cycles off; and 30 cycles on to avoid splash at the start but finish with plenty of upset. This setting produced good results on a particular job, but any variation, even of one or two cycles, affected the finished results.

The spot welding of large frame assemblies requiring portable resistance welders (Gun Welders) illustrates one of the outstanding benefits. There are definite limitations as to size of this equipment in order to engage the work and for portability, yet two and three thicknesses of structural steel $^1/_8$ up to $^3/_8$ in. thick can be welded on a production basis.

All material is cleaned of rust and scale and plenty of water is used to cool electrodes and cable. Data for these jobs are entered as Jobs 18, 19 and 20 in Table 18. The values are typical but vary with the set-up and fit of the parts. Table 18 gives data collected from other applications where pulsation welding proved superior. Low Carbon steel has a wide plastic range for suitable welding results. The irregularities are due to this and to different people's work on different machines.

On Job 4, 4 x 8 pulsations means that the control was set for 8 automatic pulsations and was refired 4 times. Jobs 9, 10 and 17 each used one large flat tip to avoid marking the one surface.

Table 19 gives similar data for some projection welding jobs on which pulsation welding proved advantageous.

For a choice of settings to be made for a job different from any described, choose a certain ratio of "off" time to "on" time depending on the material and its thickness. With steel it is deemed proper to use equal times "on" and "off" for $^1/_4$-in. and $^3/_8$-in. stock, with a smaller ratio of time "off" for thinner steel and a greater ratio of time "off" for thicker steel. This rule serves for steel only. For spot welding aluminum or aluminum alloys the "off" time must be held to a very few cycles because of the high thermal

conductivity. The ideal timing would keep the electrode contact surfaces cool without cooling the weld zone. Try to pick the best compromise.

Table 18—Welding Technique—Pulsation Spot Welds

Job No.	Tip Diam., In.	Pressure, Lbs.	Amp.	Cycles On	Cycles Off	Number of Pulsations	Material
1	3/8	430	16,000	4	2	8	1/8 to 1/8-in. steel sheet
2	3/4	2,600	37,000	5	5	10	1/4 x 2-in. steel bars together
3	3/4	4,000	42,000	7	7	17	3/8 x 2 1/2-in. steel bars together
4	1	11,500	73,000	20	50	4 x 8	1 x 3-in. steel bars together
5	1/2	1,000	20,000	10	9	13	1/4 x 2-in. steel angles together
6	1/2	2,850	32,000	9	14	9	1/4 x 2-in. steel angles together
7	7/16	1,350	13,300	13	16	5	0.093-in. clip to 3/16 x 1-in. steel bar
8	3/4	4,000	45,000	20	50	6	1/8-in. + 1-in. + 1/8-in. steel plates
9	7/8 and 2	7,000	70,000	9	20	3 x 10	1/4-in. plate to 3/4 x 3-in. steel bar
10	7/8 and 2	7,000	73,500	9	20	6 x 10	1/4-in. plate to 2 x 3-in. steel bar
11	5/8	4,000	36,000	11	8	10	1/8-in. + 1/4-in. + 1/2-in. +1-in. + 1/4-in. + 1/8 x 2-in. steel bars
12	5/8	5,500	64,000	11	5	7	117 0.044-in. steel laminations
13	3/4	3,300	58,000	13	31	5	19 1/8-in. sheets, steel stacked
14	5/16	1,500	21,800	10	6	3	2 sections 3/32-in. Zamac No. 3
15	11/16	4,000	86,000	22	50	4	1/2 x 2-in. bars, 65–35 brass together
16	8° cones	1,200	35,000	4	2	6	1/8 to 1/8-in. duralumin
17	1 1/2 in. and 15°	2,200	56,000	5	2	12	1/4 to 1/4-in. duralumin
18	1/2	2,800	30,000	15	10	5	1/8 to 1/8-in. structural steel
19	1/2	2,800	30,000	20	10	10	3/16 to 3/16-in. structural steel
20	1/2	2,800	42,000	20	10	15	1/4 to 1/4-in. structural steel

Cycles of current flow 60 per second alternating current.
All surfaces clean. Heavy scale removed by steel grit blast.
Electrodes used were made of R.W.M.A. Classes 1 and 2, Alloys.

Percussive Welding

Description.—The principle of percussive welding is defined as a resistance welding process wherein a relatively intense discharge of energy and

Table 19—Pulsation Projection Welding Technique

Job No.	Projections	Electrodes and R.W.M.A. Class No.	Lb. Pressure	Amp.	Cycles On	Cycles Off	Impulses
1	$1^5/_{16}$-in. diam. x $^1/_{16}$-in. high ring on nut to $^1/_{16}$-in. sheet steel	Copper Pocket Flat No. 2	5400	71,000	2	2	4
2	8 proj. 0.040 x $^5/_{32}$ x $^7/_{16}$ in. on $^3/_{16}$ x 1-in. bracket to $^1/_8$ x 1-in. steel ring	No. 2 No. 11	1600	83,000	5	3	8
3	Brass to steel crossed 5-gage wire	Notched No. 1	400	...	2	4	4
4	Brass $^3/_{16}$-in. diam. wires crossed	Notched No. 1	400	...	3	3	6
5	0.012 x $^1/_4$-in. diam. dome on 0.044-in. Red Brass to 0.044-in. steel	No. 12	550	13,200	5	2	5
6	0.010 x $^{11}/_{32}$-in. ring in 0.020-in. steel to $^1/_{32}$ x $^5/_{16}$-in. Ni silver strip	No. 12	295	16,400	3	11	12

the application of high pressure (usually a hammer blow) occur simultaneously or with electrical discharge occurring very slightly before the application of the pressure of the hammer blow.

There are several variations of this process which are in some ways sufficiently fundamental to produce definitely different characteristics in the resultant weld.

Considering these variations in the order of their invention, the first method, as invented by L. W. Chubb, utilized a low-voltage condenser connected to the two pieces to be welded and an electromechanical device for moving the pieces through the required pressure cycle. Since the energy contained in the condenser was at low potential, it was necessary in this process to first bring the work together, second, start the discharge of the condenser, third, draw apart the parts being welded practically simultaneously with the discharge of the condenser in order to create an arc between the parts and thus obtain a partial surface melting of the parts, and last, or fourth, bring the parts together again with a heavy impact blow.

This process was limited first, by the amount of energy which could be contained in a reasonably dimensioned low-voltage condenser and second, by the complexity of the mechanism required for the cycle of applying the current, drawing the parts apart and then clamping them together with an impact blow, all of which had to be done with accuracy, precision and speed.

It was principally used for butt welding together small diameter wires. A subsequent improvement of this process made by Chubb replaced the condenser with an electromagnetic field, produced by sending direct current through the primary of a transformer. Upon interruption of the current the collapsing field induced current in the secondary winding, which was connected to the parts to be welded, and started the same mechanical cycle

of striking an arc between the parts welded by drawing them apart and then forcing them together with an impact force.

This improvement allowed use of a greater source of energy than could be conveniently contained in a low-voltage condenser but still had the disadvantage of a complicated mechanism for producing the cycle of operation, which now had to be timed and executed even more accurately

A third and more practical form of percussive process invented by F. C. Vang consists in replacing the low-voltage condenser or electromagnetic field with a high-voltage condenser possessing potential sufficient to break across an appreciable air gap and thus obviate the necessity of first drawing apart the parts being welded in order to discharge the energy at the weld.

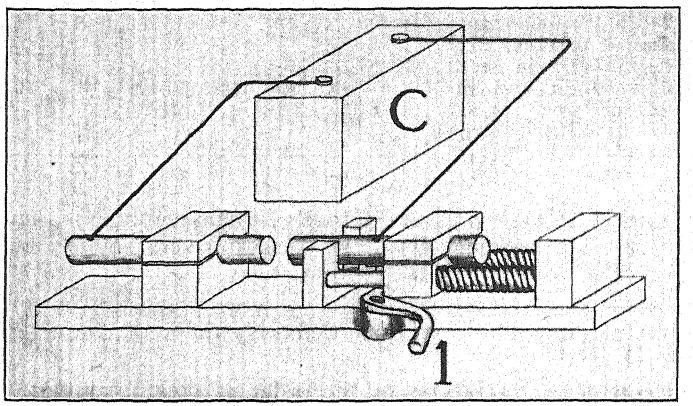


Fig. 42—Schematic Diagram: Percussive Welding Process as Developed by Vang

Figure 42 shows a simple sketch of the principle utilized by the Vang process. Condenser *C* charged to several thousand volts potential is directly connected to the parts being welded which are held apart by latch *l* against the force of a spring or an air piston. Upon the release of latch *l*, the parts are propelled together at a high rate of speed. However, before contact between the parts is established, the electrical energy contained in the condenser is discharged through the air between the two parts, creating a high-energy arc.

By judicious design of the electrical and mechanical characteristics of the circuit, a high-intensity arc can be produced of such short duration that its effect upon the parts being brought in contact is purely superficial—that is, only a surface layer of a few thousandths of an inch thickness on each part reaches a molten state.

The Vang process, at present probably the most common form of percussive welding, has certain accomplishments not found in any other welding process.

To understand the operation of this process it must be remembered that the duration of the arc is a matter of less than 0.001 second, while the power

expended in the arc is in the neighborhood of from 200 to 300 kw. Because of this and of the fact that all of the weld energy comes from this arc, the electrical resistance of the parts to be welded does not affect the amount of heat generated at the weld and substances of entirely dissimilar characteristics can be readily welded, as for instance, stainless steel to aluminum or copper. In fact, it makes no difference what either the electrical resistivity or the melting temperature of the part joined is as long as it is a reasonable conductor of electricity.

Furthermore, the extreme brevity of the arc confines fusion to the surface of the parts welded and results in almost complete absence of flash.

Figure 43 shows a microphotograph of a copper to steel joint while Fig. 44 shows a destructive test made on a steel stud joined to a disk by this process.

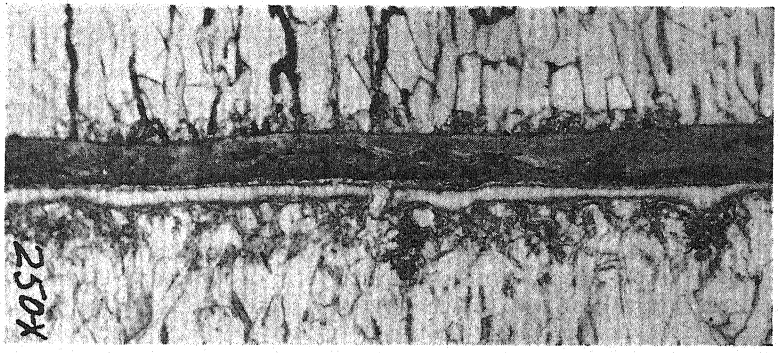


Fig. 43—Microphotograph of a Copper to Steel Joint Made by Vang Process. Total Thickness of Weld and Heat-Affected Zone Is Less Than 0.010 In.

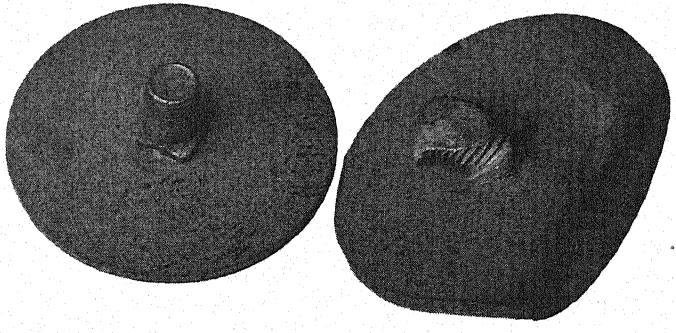


Fig. 44—A Destructive Test of a Weld Between a Square Steel Stud and Disc

Application.—It must be remembered that all percussive processes are confined to butt-welded joints. In addition, since control of the path of any arc is difficult, the total area that can be joined at any one time is limited for best results to not over $^1/_2$ sq. in., and then only when it is

reasonably concentrated. It has been found that on larger sections the arc fails to distribute itself uniformly over the entire area and cold or unwelded spots result in parts of the joint.

In general it can be said that the process is suitable for joining pieces of rod, tube or pipe either to each other or to flat surfaces. Since this can be also accomplished more economically by the ordinary butt-welding process, the percussive process is further confined to either joining parts of completely dissimilar metals such as would not be normally considered weldable by the ordinary butt-welding process, or (in case of Vang process only) of parts where complete lack of flash is imperative.

An additional and rather obvious limitation of this process is that the parts to be joined must be separate, that is, a ring or a band cannot be formed by joining the two ends together.

Stored Energy Welding

General.—Stored energy welding is defined as a resistance-welding process wherein the electrical energy required to produce the weld is accumulated in a suitable storage reservoir, usually at a low rate, prior to its transfer to the weld, and usually delivered at a high rate.

Strictly speaking, the percussive weld as described in the preceding section is a stored energy weld. The term stored energy welding, however, is more commonly used to denote a modified form of spot or projection welding process and will be used as such here.

Depending on the specific application, there may be a number of reasons why the intermediate step of energy storage may become desirable in a spot-welding process. Of these, two are most common: the first is poor voltage regulation of the power supply, and the second, the unusual form of welding power deemed desirable for some materials.

The first reason is fairly universal as in the modern trend to high-speed, short-time welding, a voltage variation of over 10% can frequently be disastrous to good welding. It is then often more economical to install the intermediate stored energy reservoir at each spot welder rather than to attempt to eliminate the voltage variation on the power system.

The second reason applies most often in cases of metals of extremely high thermal and electrical conductivity where it is considered desirable to weld with an extremely high impulse of current in a very short time. Although a similar current impulse can be produced directly by means of an ordinary alternating current, either by taking a half cycle of a 60-cycle wave, or by inverting and superimposing several adjacent cycles of a three-phase 60-cycle wave, this is apt to result in an extremely high kva. demand, which is frequently undesirable. Furthermore, the shape and hence the heating cycle of a 60-cycle wave is fixed fairly rigidly while the stored energy can be discharged in a variety of wave shapes so that any reasonable heating cycle can be obtained inside the spot weld.

This characteristic makes the process particularly useful in cases of aluminum or other high conductivity alloys where it is frequently deemed desirable to have an extremely rapid current rise with a subsequent rapid

decay for welding of light gages and a much lower rate of the current rise and decay for heavier gages.

The kva. demand of stored energy welders is a function of the secondary current output desired and of the operating speeds in spots per minute. Thus the higher the secondary current output and the faster the operation, the higher the kva. demand. However, with normal operating speeds and reasonable spot welding techniques, comparatively low kva. demands of 25 to 100 kva. can be obtained.

Table 20 gives a typical kva. demand in terms of aluminum gage thickness and spots per minute for an electrostatic or capacitor type of stored energy welder. It is, however, in general, typical of the electromagnetic type also except for the speed of operation which is about twice as great in the case of the condenser types as in the electromagnetic type for the same kva. demand.

Table 20—Aluminum Alloy Sheet When Welded in a Two-Ply Combination and Kva. Demand for Capacitor Type Stored Energy Welder

Stock Thickness, In.	Operating Speed Spots/Min.	Kva. Demand
0.020	110	40
0.035	90	40
0.060	70	50
0.080	40	50
0.125	10	70

Method of Operation.—The most common method of storing energy, namely that of an electrochemical battery, is obviously not suited for welding purposes as the switching problems and the economies involved in controlling and producing currents of the magnitude suitable for resistance welding would be almost unsurmountable.

The two other most common methods of storing energy, namely in electrostatic and electromagnetic fields, are both used for electrical storage welders. They both have their advantages and limitations—the principal advantage of the electromagnetic principle being that of simplicity, while the principal advantages of the electrostatic principle being that of greater current capacity and flexibility of the wave shape.

As both of these systems are used quite extensively particularly for welding aluminum alloys, they are described in the following section to some extent.

Electrostatic Method

The principle of electrostatic method of stored energy welding is illustrated in Fig. 45. It will be seen that it consists primarily of a suitable capacitor, means for charging this capacitor to a predetermined voltage and means for discharging the capacitor through a suitable welding transformer.

For practical reasons, it is generally considered necessary to utilize a fairly high-voltage capacitor, the most common voltage value used varying from 1500 to 3000 v. Theoretically, a considerably greater amount of energy could be secured in smaller space, by using still higher voltages. However,

even if suitable capacitors were developed and available for this work, the insulating problems arising with high voltages would probably nullify the gains obtained by their use.

The spot welder itself is fundamentally similar to the ordinary type of spot-welding machine with the exception of the welding transformer which has an entirely different turn ratio since its primary voltage is many times that of a conventional a.c. welder.

In addition spot-welding machines, primarily intended to weld aluminum, are frequently equipped with different kinds of variable or low inertia pressure mechanisms which are deemed desirable for welding aluminum. These, however, are not indispensable to the operation of this type of equipment although they undoubtedly add greatly to the success of the process in so far as aluminum alloys are concerned.

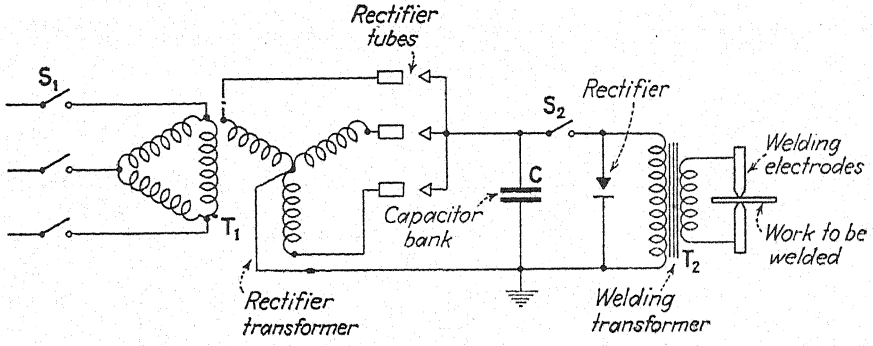


Fig. 45—Schematic Diagram: Electrostatic or Condenser Discharge Type of Stored Energy Welder

Figure 46 shows a typical spot welder designed for use on aluminum alloys, together with suitable capacitor discharge cabinet.

Figures 47, 48 and 49, show oscillograms of the secondary currents obtained from capacitor discharge type welder equipped with a rectifier shunt which eliminates the oscillation which would be normally present. They illustrate the flexibility of the current wave shape and show the effects on the current wave of variations of capacitance, voltage and turn ratios, respectively.

As mentioned before, the principal advantage of the capacitor type stored energy welder is its ability to deliver a current wave of almost any shape—the variation in the rate of current rise and decay being easily adjustable by a few simple changes in the rating (in microfarads) of the capacitor, turn ratio or capacitor voltage.

In addition, the capacitor type stored energy welders can be made to deliver an almost unlimited amount of power by simply varying the amount of capacitors used. An indirect limitation exists in the fact that the welding transformer must possess sufficient iron to prevent saturation at large or long secondary currents. Thus it is not practical to operate a

machine designed for normal operation at several hundred microfarads of capacity with several thousand microfarads of capacity. With the properly designed transformers, however, the output of any one machine is only limited by the number or the voltage of the capacitors used with it.

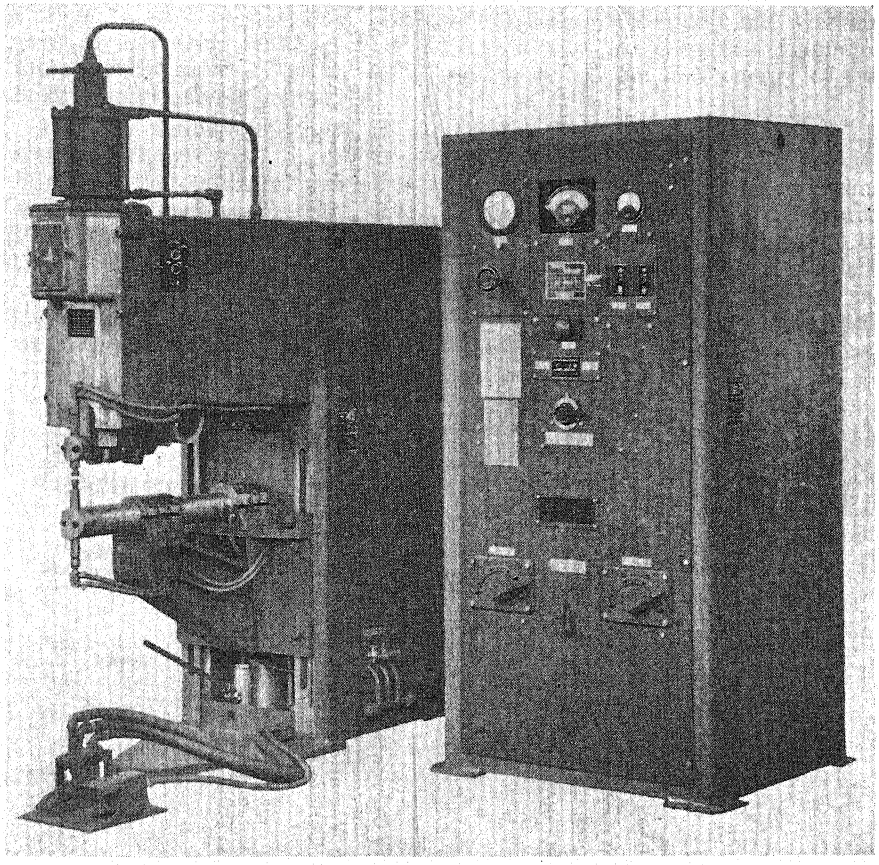


Fig. 46—Typical Electrostatic or Condenser Discharge Type Stored Energy Welder and Control

Electromagnetic Method

Operation.—The principle of electromagnetic method stored energy welding is illustrated on Fig. 50. As in the Chubb percussive process, the source of energy is in the electromagnetic field produced by sending direct current through the primary of a suitable welding transformer. Upon interruption of the direct current the field sustained by the flow of the current collapses and the energy stored in the field is transmitted to the secondary winding of the transformer and dissipated in the resistance of the secondary circuit.

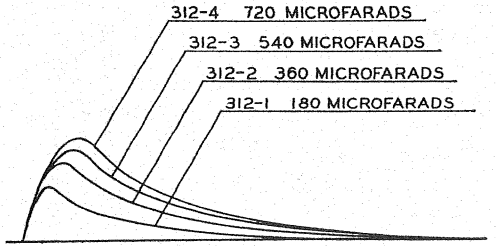


Fig. 47—Oscillogram of Secondary Currents Obtainable with Condenser Discharge Stored Energy Welders Showing Variation Produced with Changes in Condenser Capacity

Condensers charged to 2000 v. in all cases. 300:1 Transformer turn ratio. Maximum peak current shown 35,000 amp. reached in 0.012 sec.

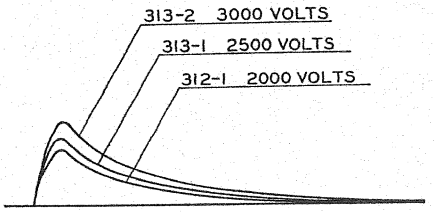


Fig. 48—Oscillogram of Secondary Currents Obtainable with Condenser Discharge Stored Energy Welders Showing Variations Produced with Changes in Condenser Voltage

180 Microfarads condenser and 300 : 1 Transformer turn ratio in all cases.

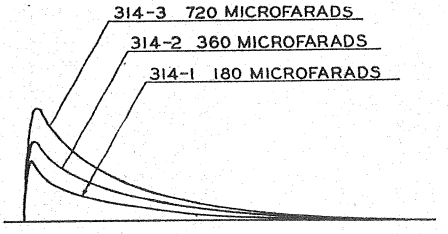


Fig. 49—Oscillogram of Secondary Currents Obtainable with Condenser Discharge Stored Energy Welders Showing Variations Produced with Changes in Condenser Capacity

Condenser charged to 2000 v. in all cases. 150 : 1 Transformer turn ratio. Maximum peak current shown 40,000 amp. reached in 0.004 sec.

The unit energy stored in any magnetic field is represented by the area above the magnetization curve of that field plotted as density in gausses against gilberts per centimeter. Figure 51 shows the typical magnetization curves for closed and nearly closed transformer iron circuits. Curve 0 represents a closed iron circuit without any air gap. It will be seen that for any field intensity, the area above this curve is comparatively small. Curves 1 and 2, respectively, represent the same iron circuit but with air gaps of increasing length. It will be seen that for the same magnetic intensity the area above the curve and therefore the unit energy of the field is progressively higher.

For any definite magnetic circuit there is an optimum air gap which results in the greatest capacity for energy storage in this particular circuit. For good grade of transformer silicon steel and normal design the optimum air gap will vary between 2 and 4% of the total length of the iron circuit. Very roughly, depending on the method of energy recovery and design of the circuit, it can be stated that in a well-designed electromagnetic system and with the optimum air gap, between 2 and $2^1/_2$ watt-seconds can be stored and subsequently recovered in each pound of iron of the core of the welding transformer.

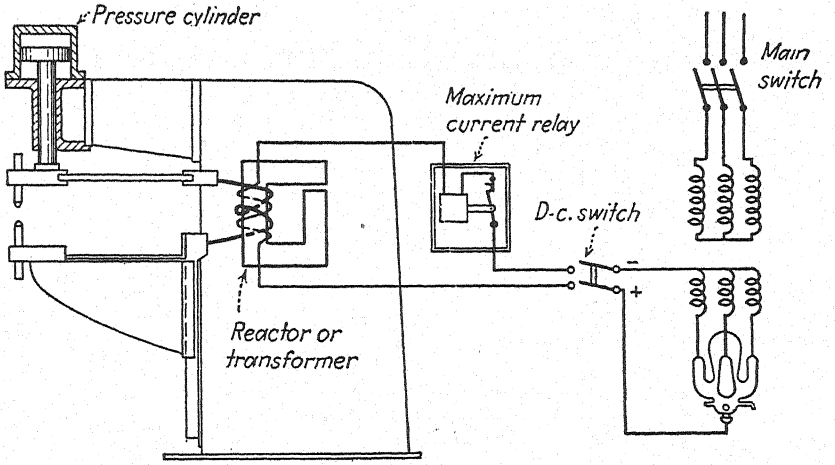


Fig. 50—Schematic Diagram: Electromagnetic Stored Energy Welder

It will be noted that the use of this energy is contingent upon its proper recovery from the electromagnetic field which is effected by the interruption of the primary current supporting the electromagnetic field. Since the collapsing electromagnetic field will attempt to maintain the primary current as well as to establish the secondary current, there will be a strong tendency on the part of the current interrupting switch to arc and unless means are provided for promptly extinguishing this arc, it will maintain itself and absorb a considerable part of the available energy. By interposing several contactors in series, which progressively insert increasing resistance into the primary circuit, the primary current can be interrupted with suf-

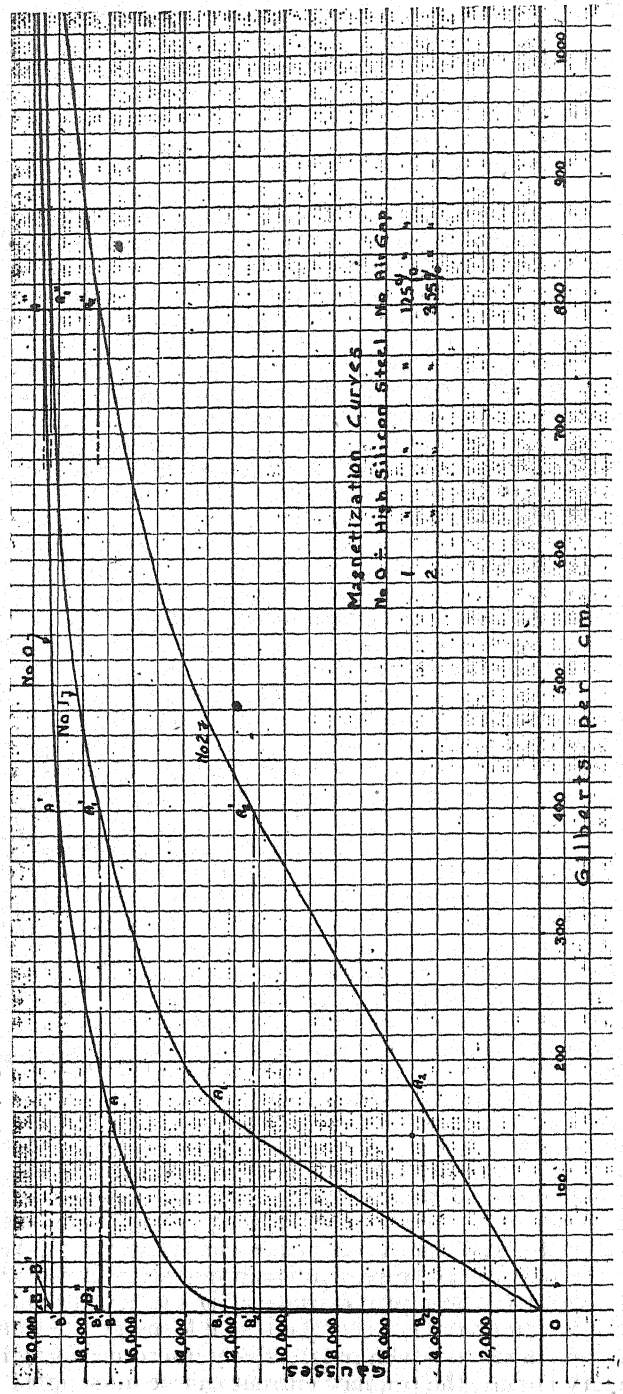


Fig. 51—Magnetization Curves for High Silicon Steel Circuits with No Air Gap and 1.25% and 3.55% Air Gaps, Respectively

ficient rapidity to recover in the secondary current most of the energy stored in the field.

However, it must be always remembered that in the machines operating on this principle the output is a function of the speed and efficiency of the extinguishment of the primary arc and any change in the operation of the current interrupting device will affect the output of the welder.

It will be seen from Fig. 50 that during the time of the establishment of the primary current in the welding transformer a current will flow through the secondary circuit, the magnitude and duration of which will be a function of the speed with which the primary current is established, i.e., of the primary kva. drawn by the machine during its charging cycle. In some form or another it is characteristic of this type of stored energy welder and cannot be dispensed with, under practical conditions, though its duration can be reduced to almost any time, by a suitable increase of the charging potential and hence of the kva. demand.

From the welding point of view this charging, or as it is sometimes known "preheating current" may or may not be beneficial depending on the welding characteristics of the material being welded. From the point of view of the speed of operation of the welder, however, it introduces a time interval, which may be as high as 1 sec. and is seldom less than $^1/_2$ sec., between the time pressure is applied to the electrodes and the time the discharge of the welding current begins.

It will be seen from Fig. 50 that the fundamental circuit of the electromagnetic method is very simple, consisting essentially of a suitable welding transformer, a source of direct current and suitable means of interrupting the primary current. The most complicated part of the entire apparatus is the means for interrupting the primary circuit. On most machines it consists essentially of from four to eight magnetic contactors timed to open successively one after the other in a very short time, the opening of each contactor inserting a progressively larger block of resistance into the primary circuit until infinite resistance is reached at the last step.

The magnitude of the secondary current peak is controlled by varying the magnitude of the primary current at the time of its interruption. This is usually done by means of a special current overload relay which actuates the current breaking mechanism when the charging current reaches a predetermined value.

The primary advantages of the electromagnetic method are first its simplicity, and second, the preheating current which under certain conditions is claimed to be beneficial.

The disadvantages of the electromagnetic system are first, its limitation in so far as the magnitude of the secondary current output is concerned, and second, the inherent inflexibility of the wave shape of the secondary current.

The limitations in the secondary current output are usually overcome to some extent by the variable pressure cycle usually present on these machines which consists of means for welding at low pressure thus utilizing to a large extent the contact resistance between the surfaces welded, and then forging it under high pressure, which eliminates to a large extent the trouble encountered in low pressure welding.

Figure 52 shows a photograph of a modern electric storage welder utilizing the electromagnetic method. The photograph does not show the rectifier unit which is usually furnished in a separate cabinet whenever direct current is not available. The rectifier unit usually converts three phase power of 220 or 440-v. potential to direct current of from 100 to 200-v. potential.

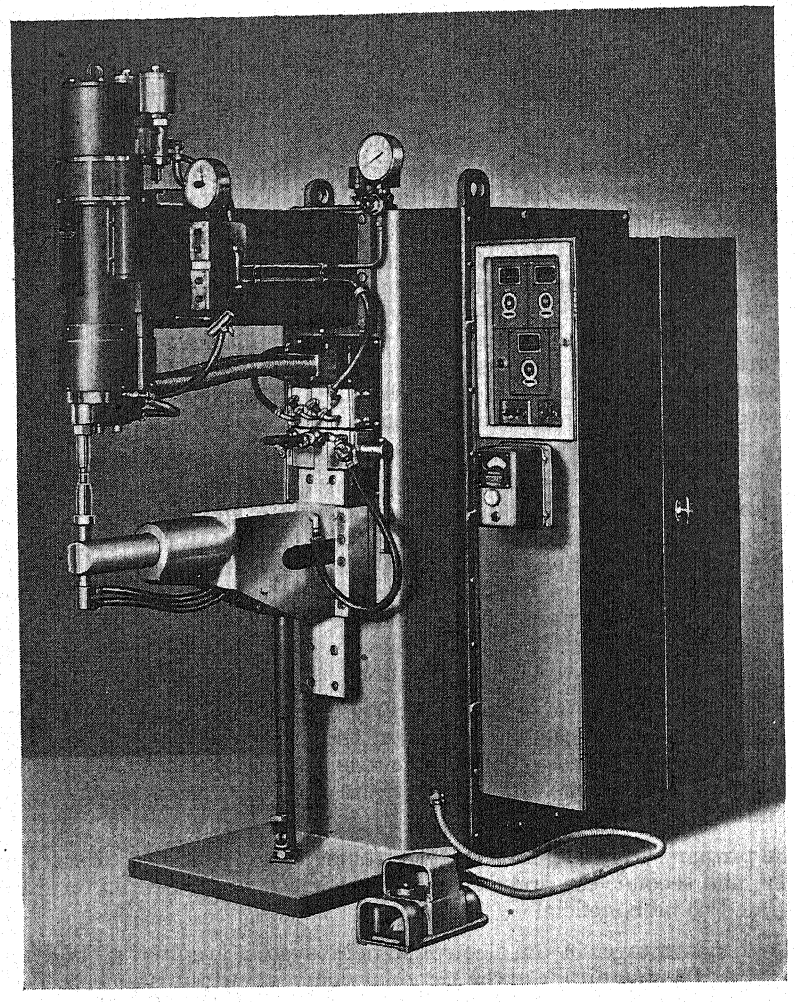


Fig. 52—Stored Energy Welder of the Electromagnetic Type

Electric Resistance Brazing

Electric resistance brazing, or Electro-Brazing, is the application of heat and pressure to the parts to be joined, or to the dies holding these parts, by their resistance to the passage of current, following the same general fundamentals of electric resistance welding.

The equipment used, in most cases, is identical to that used for resistance welding.

Stationary Equipment

This equipment is usually in the form of a Press Welder, and the control of the electrodes for motion and pressure is effected in the usual manner.

Brazing Presses are usually equipped with a larger transformer than for welding, and the secondary circuit is made to carry the maximum current, without undue heating, and the electrodes, dies or holders sometimes are water cooled.

Current Supply

For general application alternating current is used as there is no simple method of obtaining direct current in the amperage required. The current is applied from a transformer designed to give the required voltage. Brazing transformers are wound to take current from power lines and deliver current at low voltage to the brazing dies.

Electrodes

Carbon and graphite are used, because of their high resistance, although electrodes made from tungsten and other high-resistance materials, are also used. Three grades of carbon electrodes are available designated as "soft," "hard" and "extra hard."

Soft.—Electrical resistance 0.0007 ohm per inch cube. This type has a low surface resistance, thereby practically eliminating the danger of overheating the work in spots or "burning" the surface of the work from too rapid heating. It should be used in all cases when brazing metals or alloys having a high thermal resistance, particularly with respect to steel and steel alloys. Due to the low resistance of the electrodes, the current requirements are correspondingly high. Current densities up to 1500 amp. per square inch of contacting surface are commonly used.

Hard.—Electrical resistance 0.0012 ohm per inch cube. This type of electrode has a surface resistance considerably greater than that of the "soft" type. Its advantage over the soft type is that brazing temperatures can be had with approximately 30% less current. The heating of the tongs and leads is considerably reduced. Larger joints can be made with the same transformer and tong equipment and joints can be heated more rapidly. Current densities up to 1200 amp. per square inch of contacting surface are sometimes used.

Extra Hard.—Electrical resistance 0.0018 ohm per inch cube. This type of electrode has the highest resistance so far safely used. Its surface resistance is correspondingly high and the danger from "burning" or overheating joint surface is such that it should be used only by well-trained operators. Its very great advantage over the soft and hard types lies in the fact that top brazing temperatures are reached with approximately 50% of the current required by the soft type. This means that comparatively large joints can be made with standard brazing equipment. Current densities up to 800 amp. per square inch of contacting surface are commonly used.

Mountiug of Electrodes.—The life of an electrode depends to a considerable extent on how it is secured in the holder and on the uniformity of current flow. It is advisable to securely fasten the electrode in some type of holder, so that the contacting surface is held firmly against a current conductor.

Power Supply Leads.—These leads are usually made of such capacity that normal load is carried without appreciable heat rise. For convenience in handling, a two-wire cable is used with insulation.

Brazing Tongs

Tongs hold the brazing electrodes, conduct current to the electrodes and act as clamps to hold assembled joints in position and provide pressure through the electrodes. Tongs are designed for portable application; they can be used for stationary operation or can be brought to the work. As joints to be brazed are almost infinite in variety and form and may occupy inaccessible positions, tongs must be designed for minimum weight and size. The weight depends upon the amount of pressure required to clamp the joint and the amount of current required to heat the electrodes. The size of tongs is determined by the area of the joint and the form usually by the joint location.

Tong Leads.—These leads are intended to be operated at high current densities. If the lead capacities followed standard ratings, they would be so heavy that operation of the brazing tongs would be very difficult. They should be made of flexible cable. Extra flexible is commonly used. Bare cable is used, wrapped with asbestos tape and coated with water glass or shellac varnish. When bare cable is not obtainable, strip the insulation from standard insulated cable and proceed as for bare cable.

Brazing Procedure

There is a certain definite procedure that must be followed to insure satisfactory work in making a silver alloy brazed joint.

Point 1. Cleaning.—Parts to be brazed should be mechanically or chemically cleaned. Grease, oxides, scale and dirt of any kind should be removed.

Point 2. Fluxing.—The function of flux is threefold: (1) It offers a protective coating which tends to prevent oxidation; (2) it dissolves oxides that form while heating; (3) it assists in the free flow of the alloy. There are two steps to keep in mind when fluxing: (*a*) Before heating, brush the flux on the joint area where the alloy should flow. (*b*) Apply flux to the brazing alloy. In applying flux, do not cover the entire surface. Leave a bare spot to assure a metal-to-metal electrical contact to start the current flow. Dry flux is an insulator.

Alloys.—Over a period of time, the following silver alloys have found the greatest common usage:

1. This alloy contains 15% silver, 80% copper and 5% phosphorus. It melts at 1185°F. (641°C.) and flows freely at 1300°F. (700°C.). It is widely used in making lap joints between copper to copper, copper to brass and brass to brass. It should never be used on ferrous metals or alloys. In joining copper to copper, because of the phosphorus content, no flux is required. In joining copper to brass or brass to brass a thin film of flux should be applied to the work.

2. This alloy contains 50% silver, 15½% copper, 18% cadmium and 16½% zinc. It melts at 1160°F. (627°C.) and flows freely at 1175°F. (635°C.). Metals and alloys that can be joined include practically all ferrous and non-ferrous metals that can be heated to 1200°F.

3. This is an alloy containing 50% silver, 34% copper and 16% zinc. It melts at 1280°F.(693°C.) and flows freely at 1425°F. (774°C.). This alloy is used in making butt joints on copper because of its low electrical resistance and high ductility.

4. This alloy contains 30% silver, 38% copper and 32% zinc. It melts at 1370°F. (743°C.) and flows at 1410°F. (766°C.). In fabricating parts it is often necessary to make the first joint with this alloy because of its higher melting point. Subsequent joints can then be made adjacent to or on top of the first joint with a lower melting point alloy, without disturbing the first joint.

Forms of Silver Brazing Alloys.—Due to the high degree of ductility and malleability of silver brazing alloys, they can easily be fabricated into a wide variety of sizes and shapes, making it possible to obtain them in the forms most convenient and economical for different conditions.

Types of Brazed Joints

The principal factor to be considered in the electrical design of a joint is that of the electrical conductivity. It can be readily understood that a joint should have no greater electrical resistance than the resistance of the joint members themselves. In other words, a joint should not add electrical resistance in a circuit. From an electrical standpoint, all joints can be included under the following three types: butt joints, lap joints, solidified joints.

Butt Joints.—It is always desirable to avoid butt joints, but where conducting strips have to be joined without increasing the cross-sectional area, butt joints must be used. There are two general types of butt joints: straight, or square butt joints and scarfed butt joints.

Straight or Square Butt Joints.—With this type of joint the members to be joined are squared so that both members have their cross-section areas in complete contact.

Scarfed Butt Joints.—Two types of scarfed joints are used. The most common type is made with scarfed surface forming an angle with the flat of the conductor strip. The scarfed dimension usually forms a lap equal to the thickness of the strip when thickness is ⅛ in. and under. With heavier strips the angle is two, and in some cases three times the thickness. The other type is made by the scarfed surface forming an angle with the edge of the conductor strip. The dimension of the scarf is usually equal to the width of the conducting strip, but may be less or greater to suit certain conditions. With this type of scarfed joint there is no advantage in strength, but there is an increase in ductility and conductivity.

Solidified Joints.—When cables, braid groups and laminated lead ends are filled with brazing alloy, they are said to be solidified. In making solidified joints or sections, it is the usual practice to heat the parts under light pressure and to increase the pressure as the temperature increases. By following this method, the complete solidification of the joint is assured. A properly solidified joint can be machined and treated much the same as a solid mass. When cables, braid groups or laminated leads have to be brazed to the terminal conductors, the solidification and all brazing should be done simultaneously—never heat such material more than once if it can be avoided.

Applying the Brazing Alloy

Basically, there are two ways of applying the alloy:

1. The silver brazing alloy may be preplaced between the joint members in the form of a wire, sheet or filings.

2. The silver brazing alloy may be fed by hand to the joint boundaries in the form of a rod or wire, after the joint has reached the brazing temperature.

Where alloys can be preplaced, there are a number of advantages, such as:

(*a*) The flowing of the alloy automatically indicates the proper brazing temperature.

(*b*) The amount of alloy per joint can be predetermined and the cost controlled.

(*c*) It insures the homogeneous filling of the entire joint area.

Controlling Heat Flow.—Since electric resistance brazing is free from open flame, joints can be made very close to insulation. Also, because of the rapid heat input, restricted practically to the joint area, joints can be made without fear of damaging adjacent insulation. When the heat flow must be limited to a very close area, adjacent insulation may be protected by wrapping with damp asbestos putty or tape. Heat is readily controlled by applying the current intermittently so as to balance the heat throughout the joint until the proper temperature is reached.

Advantages of Electric Resistance Brazed Joints

1. Because of higher heat rise allowable on electrical joints, engineers can design lighter sections and make substantial savings on raw material.

2. The use of tinned wire is not required and savings can be made. Joints do not require pretinning.

3. Joints can be made faster than either a mechanical or soft solder joint and cost less.

4. Because of greater strength of alloy in shear than in mechanical or soft solder joints, joint lap can be reduced, saving raw material.

5. The reduced lap required and localized heating make it possible to join parts close to insulation and supporting members. Also, because parts generally can be made of lighter materials, over-all weight and size of finished apparatus can be reduced.

CHAPTER 10

RESISTANCE WELDING MACHINES*

Installation, Servicing, Guide to Good Electrical Performance, Current Output and Impedance, Jigs and Fixtures, Portable Welders and Fixtures Used with Portables.

INSTALLATION

THE installation of resistance-welding equipment is comparable to the installation of other machine tools, with the single exception of the power supply for the welding transformer.

Resistance-welding machines present an electrical load of intermittent character, high magnitude and poor load factor. Because of these inherent characteristics, the providing of adequate electric service, both from the standpoint of plant electrical distribution and the power system supply, merits special consideration.

With the proper power supply available, and water and air lines brought to the approximate vicinity of where the welder is to be placed, the first requirement is to set the welder on a firm foundation and fasten it to the floor with lag screws.

The electrical connections for the welding transformer (single phase) require suitable size wire in conduit to a Safety Disconnect with overcurrent protection being provided by either a double pole, single throw, fused knife switch or an automatic circuit breaker. A good ground connection to the machine base is essential.

The electrical connections for motors on motorized equipment (usually three phase) require suitable size wire in conduit to a Safety Disconnect of the usual standard recommendation.

The water supply for standard equipment is provided by a pipe and shut-off valve of not over $^3/_4$-in. size. A $1^1/_2$-in. drain line runs to the nearest sewer connection. Water supply must be free from mineral and organic deposits, which will in time clog the cooling circuit.

The air supply for standard equipment is usually provided by a $^1/_2$-in.

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pipe with shut-off valve and strainer. For booster units a larger size will be required. It must be noted that for the so-called "Air Lock" or "Air Cushion" welding pressure control, no air is consumed, as none is exhausted with this arrangement.

It is extremely important to first check the name plate of the welder with the line voltage, and when connecting to the motor circuit, make certain that the direction of rotation is correct.

Where control apparatus is separately mounted from machine, the circuit diagram given with such control must be followed for connections to the machine and power line. Details of various types of controls are given in Chapter 11.

A typical installation diagram for motor-operated press type spot or projection welders is shown in Fig. 1. Similar diagrams are issued with the shipment of all standard equipment. For size of wire see Chapter 8.

For the size of the fused safety disconnect or air circuit breaker, the local power company or the welder manufacturer should recommend the proper size, since the operating duty cycle as well as the job itself determines the proper size of this overload protection.

SERVICING

Intelligent servicing or maintenance of resistance-welding equipment can only be accomplished by a thorough understanding of the principles of resistance welding and the function of the mechanical principles of the machine operation. This can be obtained through experience and study of the machine and the job and cooperation with the machine's manufacturer.

The following paragraphs cannot possibly cover all contingencies of breakdown or poor welder performance. However they will point to the more usual causes of improper machine performance which, through neglectful servicing or maintenance, lowers the ultimate production that can be obtained from the equipment.

It is important to remember to turn on the water before using the machine, since, otherwise, excess heat will quickly generate at the welding points and dies. These will become softened and, more serious, with an extended run without water cooling, the welding transformer may be seriously damaged. The water must be shut off when the machine is stopped for a period of time to prevent condensation. Automatic shut-off valves for the water-cooling system are sometimes used, insuring correct water cooling.

To operate a welder successfully with a minimum of replacement of wearing parts, it is only necessary to remember that good welding means that the proper heat and pressure, and the correct synchronization of these factors, are used, granted, of course, that the machine, welding dies, etc., are suited for the welding job.

The best results in resistance welding are obtained when the stock is clean and free from scale, rust or dirt. More heat and pressure are required for unclean or rusty stock than for clean material.

It will repay the user of resistance-welding equipment to keep the weld-

ing points or dies clean and trimmed to their original proper size, using the alloy copper specified for the job.

Secondary contacts must be kept tight and free from oxide because of the extremely high currents they must carry at very low voltage.

On air or hydraulically operated machines lack of welding pressure may be due to leaky valves or cylinder pistons. Water and dirt must be kept

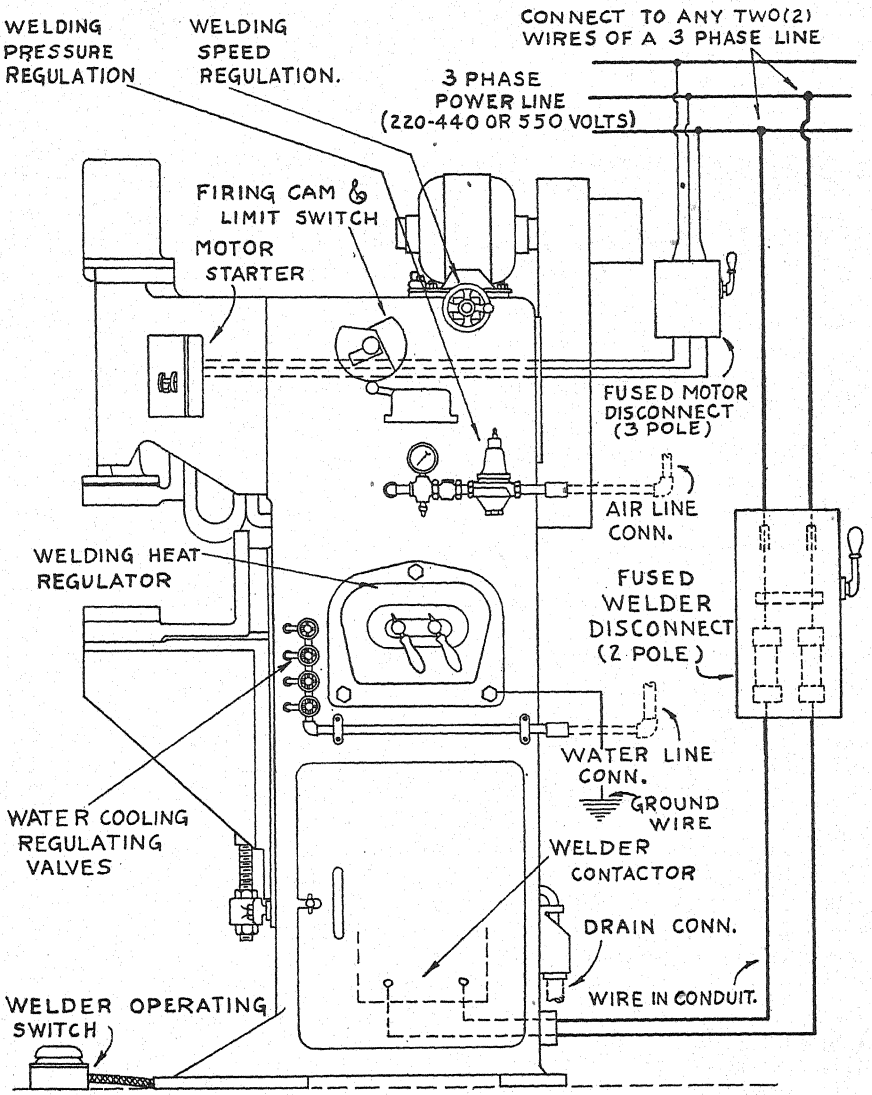


Fig. 1—Typical Installation Diagram for Motor-Operated Press Type Welder

out of air lines (by means of traps or filters) and defective parts replaced.

The parts which are subject to wear and must be replaced at intervals are welding points or dies and switch contact tips. Spare parts for these items should be kept available at all times.

It is important to remember that there is no danger from shock from the welding arms or electrodes on any resistance-welding equipment, since the voltage at the welding points is practically never in excess of 15 or 20 volts and is usually less than 5 or 10 volts. Only when servicing or inspecting the power lines, welding transformers or control circuit is danger present. Only a qualified electrician should make such inspection or repair, opening the circuit at the disconnect before proceeding.

When starting a welder for the first time, always set the heat regulator at the lowest heat, and gradually increase same as required after trial welds, keeping in mind that increased heat will allow increased welding pressure for better appearing welds or for "one pass" or scaly material.

The duration of welding time can be varied through a cam adjustment operating the firing switch on motor-driven machines, or through a weld timer if such equipment is provided. The point of firing the welding heat, through either the cam and limit switch, pressure switch or sequence control for air or hydraulic machines or manual operation, must always begin after the welding pressure application, and end before the welding pressure is released.

It is, of course, essential that all machine parts be kept lubricated and protected from the weld flash.

Hydraulically Operated Machines

Hydraulic circuits for welding equipment run from the simple circuit applied to standard press welders to a complicated circuit used on automatic welders, and they most frequently embody the principle of a constant volume and a variable pressure control. The equipment consists of either a pump, a control and relief valves as standard equipment manufactured by several hydraulic equipment specialists or the air hydraulic booster unit (see Portable Welders). The pumps or booster units are the type and of a size according to the delivery of oil required for the cylinder stroke, and the speed of operation. The relief valves are the "bypass" type with a spring plunger adjustment to automatically bypass oil to the sump at a desired pressure. In this manner, variable welding pressures are obtained for the actual welding operation.

It follows that at all times sufficient oil must be in the sump, not only to fill the pipe lines and the cylinder, but to have sufficient oil so that the circuit does not overheat in operation. Where a large volume of oil is used and the sump or reservoir tank capacity is limited, water-cooled coils are inserted to maintain the oil at a proper working temperature.

When starting a hydraulically operated machine when the oil is cold, its actuation is sluggish compared to the operation after it has been running and the oil temperature has been raised to proper working temperature.

It also follows that foreign particles such as dirt, dry paint, chips, shavings, etc., can cause a great deal of damage in the circuits and the oil

must at all times be strained thoroughly before using, and kept clean.

The relief valves and control valves have hardened and ground plungers with a very close-fitting tolerance, and at no time must the user of this equipment attempt to reface or refinish any of these parts since it can only result in a defective part, and where trouble is traced to one of these valves, a new valve should immediately be ordered and the worn or defective valve replaced.

The operating or control valves are usually solenoid operated, and before a complicated oil circuit is broken up to determine any trouble, these valves should be checked for their operation through their respective relays and solenoid coils.

Taking the simplified circuit using a motor-driven pump, the oil from the pressure side of the pump goes to the solenoid-operated valve, thence one line to the "top," of the cylinder, one line to the "bottom" of the cylinder and one line to the sump. A regulating pressure valve is inserted in the line to the "top" of the cylinder for welding pressure regulation, and a relief valve is inserted in the line to the "bottom" of the cylinder to bypass the oil so a minimum of oil pressure is used when the welding head is up and the machine is idle. This relieves the pump from operating under a heavy welding pressure load when the machine is idle. This valve is adjusted when operating so that there is merely sufficient oil to hold the head up and may take as little as 40 to 100-lb. oil pressure as compared to 500 to 1000-lb. pressure that may be used for welding pressure loads. Various check valves may be used such as one in the line to the sump and one in the line to the bottom of the cylinder to hold the pressure in these lines so the oil will not drain out of the lines when the motor is turned off, thus holding the welding head up. It follows that there may be some leakage past these check valves, and the welding head, over a period of several hours, may drop slowly. This can be corrected by replacing the check valves if necessary. However, this is not a particular item since in starting the motor again, the head will immediately rise to the starting position due to the setting of the valve holding this line open.

Seam Welders

The servicing of the standard seam welder follows exactly the same procedure as above, with the possibility of further machine adjustment for welding speed and the sequence of current interruption for the control (see Chapter 11).

It is important that the correct lubricant be used for the welding wheel bearings for which because of the presence of considerable heat, ordinary lubricant is ineffective. Gredag No. $52\frac{1}{2}$ or its equivalent is recommended.

On "knurl"-driven seam welders it is important that the proper type of knurl face and knurl pressure against the welding wheels be used.

Flash and Butt Welders

Except for the difference of physical contour and operating detail of the flash and butt welder, the same general items for servicing apply.

Flash guard hoods or ventilating apparatus, not usually included in the

equipment as purchased, are always desirable and installed where they do not detract from the speed of operation.

Perhaps, the most common failure of this type of equipment is the work slipping under the clamp pressure when the final pushup or forging pressure is applied. Special work backups or retainers will in most cases overcome this.

On hand-operated machines it will take some time for the operator to get used to the sequence of flashing or heating and then the final pushup, and failures to produce satisfactory welds at the start of machine operation after installation must be expected, while the operator is gaining experience.

Adjustment for work lineup or special dies must be constantly watched, for without proper work alignment and maintaining this alignment, poor results are bound to occur.

An air line with a push valve fastened to the machine so that the operator can blow off the welding dies periodically will lengthen the die life.

On automatic motor-driven machines, the flashing adjustment is very important. The machine speed through variable speed drive, the cam adjustment for firing control, and the moving platen adjustment for starting position—all will affect the flashing period, which should be of sufficient length to even the edges of the work by burning off the high spots and create sufficient heated material just back of the edge surface to allow this plastic area to be welded when the final pushup occurs.

The final pushup block on the operating cam is usually an insert and can be shimmed up or cut down as the work demands.

The amount of stock projecting beyond the welding dies is important. Too much projection will be inefficient and tend to heat the work too far back of the point of weld, and too little projection will cause wear on the front sides of the dies due to flashing and will also take too much heat away from the point of weld. On some jobs a different projection of work between the right-hand and left-hand platens is sometimes desirable and can be determined simply by the size of the work and the differential of heat condition that is desired.

Personnel for Service and Maintenance

Since resistance-welding equipment is a combination of both mechanical and electrical details, it follows that neither the usual electrician nor the usual shop maintenance man should be expected to assume the responsibility of continued production on the equipment. Certainly, the operator (if the full advantage of unskilled labor is to be utilized) cannot be held responsible for the continued perfect functioning of the machine.

It follows that where several or even single machine installations are made, a mechanic with a fundamental knowledge of electricity should be responsible for keeping on hand a supply of spare welding dies, contact tips or any other items needing more or less frequent replacement. Also he should be responsible for the machine's adjustment and maintenance.

All too frequently the work to be welded, due to poor forming or stamping operations, poor material or other faulty operations prior to welding, calls upon the welder to reform or straighten the work, thus welding

under very adverse conditions—all of which frequently results in continuously poor welds really not the fault of the welder or its adjustment at all.

GUIDE TO GOOD ELECTRICAL PERFORMANCE

In order that a resistance-welding machine may operate efficiently and deliver its rated output of welding current, it is essential that an adequate power supply be provided. Proper performance with the production of consistently good welds can only be expected when correct voltage is maintained at the machine terminals.

Electric Service and Power Supply

The providing of an adequate electric service for most resistance welders is of greater moment and involves considerably more expense than that of the corresponding service for ordinary machine tool installations because of the low power factor and high-, single-phase, kva. demand inherent with this type of equipment. In many cases the cost of providing service to the machine exceeds the cost of the machine itself and, consequently, it is highly important to be sure that the machine demand is not higher than it actually need be. Where it is found that machines of the same welding-current output have different inputs because of differences in machine design, too much emphasis cannot be placed upon the selection of the machine of the lowest input as illustrated by the following example.

The welding engineer of a certain plant needs a projection welder with a maximum welding-current output of 100,000 amp. Quotations are obtained from different manufacturers on machines incorporating the desired mechanical and control features for handling the particular type of work involved. The final selection eventually is between two competing machines, each having the same mechanical features and the same method of control, but with the following differences in electrical rating:

	Machine A	Machine B
Rated kva. of transformer (50% duty cycle)	300	500
Max. open-circuit secondary voltage—volts	12	20
Max. secondary current (max. secondary voltage and min. throat spacing)—amp.	100,000	100,000
Rated primary welder voltage—volts	440	440

Welder B was slightly more expensive than welder A but the fact that it had a larger transformer at first glance indicated it to be the best machine. However, a true analysis of the cost of serving the two welders shows that welder A is the logical selection. The basic consideration, as far as welding ability is concerned, is the secondary current output and the ability of the welder to operate without overheating at a certain prescribed rate of production or duty cycle. Both welders had the same maximum current output and the productive output was guaranteed the same by both manufacturers. The larger transformer simply was needed to supply the excessive losses of machine B. The approximate kva. input for machine A is:

$$\frac{(100{,}000 \times 12)}{1000} = 1200 \text{ kva.}$$

and for machine B is:

$$\frac{(100{,}000 \times 20)}{1000} = 2000 \text{ kva.}$$

Assuming that a 1200-kva. stepdown power transformer is needed to serve welder A, it would be necessary to go to a 2000-kva. transformer for machine B for the same voltage regulation. At $3 per kva., this amounts to $2400 added investment for machine B in transformer capacity alone. Conductor costs for bus and distribution are correspondingly greater for the machine with the higher kva. input. The plant engineer who is responsible for costs of service for the welding operations will certainly select welder A as the most economical and desirable machine. The welding engineer who is interested primarily in machine output and production is equally satisfied as both machines are equal in this respect.

Limited Power Supply

There is always an upper limit of allowable kva. demand, the exact magnitude depending either upon the factory's location with respect to the power company's substations and power lines or the size of its own generating plant.

In case of power company service, the point of connection to the power company's system determines the allowable size of welder that can be handled. The sudden flow of welder current through the system impedance causes a momentary voltage fluctuation which, if of sufficient magnitude, results in lamp flicker for all lighting customers at that and nearby locations. The farther the point of service is from the main generating plants and larger substations, the greater the system impedance and resultant voltage fluctuation for a given size welder. Voltage fluctuations must be kept within accepted limits for lighting customers. These limits vary, depending upon the frequency of the fluctuation and, in some cases, if the frequency is high, such as with certain types of seam welders, the allowable voltage fluctuation may be as low as one-half volt at the lamp, and for ordinary frequencies experienced with spot, projection and flash welders may be as high as one and one-half to two volts.

Decreasing the Power Load

Whenever the kva. demand of the welder is great enough to cause lamp flicker, there are only two fundamental changes which can be made to decrease this load. The system impedance beyond the point of service common to the lighting and welder loads can be reduced or the sudden flow of current through that impedance can be reduced. There are numerous methods for accomplishing either of these changes, such as reducing the system impedance by increasing substation and line capacity, tapping the welder load direct to the transmission system, separating the lighting and welder loads and serving them from separate substation bus sections or reducing the amount of current by the use of series capacitors, synchronous

condensers, phase balancers or motor generator sets. Most of these methods involve expense of some considerable magnitude which must be passed on to the user of the welder. Obviously, if the welder is a machine of the more modern and efficient design with a kva. demand within the allowed limit for that particular location, such expensive power-system changes or the addition of corrective equipment may not be needed. It is, consequently, much to the advantage of the user of the welder to know the allowable maximum kva. demand that the power company can permit at that location and then, if at all possible, select a machine that will produce the desired welding current without exceeding this allowable kva. input.

Welders of large size can usually be served readily in large industrial areas which generally have concentrations of power quite separate from any lighting services. The main business sections of large cities do not usually have distribution facilities suitable for welders and generally the cost of providing service at such locations is prohibitive even for relatively small machines. Suburban areas and small towns are also very likely to be unsatisfactory and expensive locations except for the smaller machines.

Secondary Circuit of Welding Machine

The single, most important factor in keeping the kva. demand low is the design of the secondary circuit of the welding machine regardless of whether it is a spot, seam or other type of welder.

In order better to understand why this is so, it is only necessary to consider from the fundamental angle what is required to make a given weld. As a simple illustration, suppose a welding machine is required to spot weld two pieces of 16 gage S.A.E. 1010 cold-rolled steel. From existing engineering records the design engineer would possibly conclude that to obtain the desired quality weld, it would be necessary to limit the time to eight cycles and to pass 12,000 amp. through the parts to be welded.

The next point to be considered is the geometry of the parts to be welded since they, in turn, will dictate the minimum clearance in the secondary circuit of the welding machine which will permit properly placing the parts to be welded between welder electrodes. In this case, perhaps a 12-in. throat depth and 7-in. clearance between horns would readily admit the work to be welded. The next step is to determine the voltage necessary to cause the required 12,000 amp. to flow through this 12-in. x 7-in. secondary circuit with the work in position. This voltage might be found to be four volts which would immediately establish the kva. demand of 48 kva. If, on the other hand, a machine had been selected with a throat depth of 24 in. and a horn clearance of 12 in. because it looked as though it was plenty big enough for the work and would permit welding a larger job at some future date, a voltage as high as ten volts might have been required to give the 12,000 amp., thereby imposing a demand of 120 kva. on the distribution system and penalizing everyone concerned forever after.

From this it may be concluded that the first rule in obtaining a machine with a minimum demand for a given welding operation is to pick out a machine with a clearance that is just large enough for the work to be done,

fully recognizing the fact that if any larger clearance exists, the demand is going to be larger than it need be. There are, of course, cases where the user definitely has need for a larger throat for a certain portion of his work and he must then either put up with a larger than necessary demand on smaller parts or perhaps purchase two machines.

Having determined the throat clearance which is to be furnished in the machine, there are other factors which influence the demand, such as the actual design of the machine having this throat depth.

The prospective user of resistance-welding machines can be assured of the merit of the electrical design of the machine being considered by comparing the secondary current outputs and the kva. inputs of comparable machines. For the same secondary current output, the machine having the lowest kva. input will be the lowest impedance machine and, consequently, the most desirable from this angle. The physical geometry of the welding machine parts must be observed and the selection made, in which the transformer is placed as close to the useful throat of the machine as possible and in which the flexible connections are so arranged as not to introduce excessive reactance.

Portable Welder Power Supply

In the case of portable welding machines, the same fundamental principles apply. There is here, however, another factor to be considered and that is the type of cable used between the transformer and the gun, assuming, of course, the same principles regarding clearance have been applied to the gun as were mentioned above in regard to the throat of the welding machine. Here it is important (1) that cables no longer than necessary be selected, (2) that in the case of parallel conductors, cables be strapped closely together at all times to reduce the reactance and (3) that full consideration be given to single, low reactance, interleaved and concentric designs of cable which are now on the market and which substantially reduce the demand during weld.

Power-Supply Requirements and Welder Performance

Factory wiring and electrical distribution for resistance-welding loads must be designed on an entirely different basis from that for the ordinary power and lighting loads encountered in industrial plants. The majority of resistance-welding machines have instantaneous kva. demands several times their 50% duty cycle rating, and, in order to prevent excessive voltage drop at this equipment as well as at nearby equipment, the supply and distribution facilities must be designed on the basis of the maximum kva. demand rather than the 50% duty cycle rating of the machine. From a standpoint of voltage regulation, the supply and distribution system must be such as would normally be employed if this peak kva. demand were drawn continuously. However, due to the low operating duty cycle of this load, its heating effect on the system is usually extremely small.

Temperature Rise

Since the capacity of all power equipment and distribution systems is based on heating or temperature-rise limitations, it is seen, therefore,

that in order to serve one resistance-welding machine, the normal capacity of the system must be much higher than necessary from a heating standpoint in order to satisfy the conditions of voltage regulation. In fact, in designing a system to supply two or three or even ten welding machines operating on the usual duty cycle encountered, it is safe to neglect the consideration of heating capacity required and design the system to satisfy the consideration of voltage drop. It is only when a considerable number of machines are involved on a single system that the heating becomes a consideration of any importance, or when the duty cycle of a single welder exceeds about 25%, such as with most seam welders.

After every effort has been expended toward obtaining a welder with as low a maximum kva. input as possible, the power supply system can then be designed and installed with the knowledge that no needless capacity is being provided and that all the necessary expense is justified.

Power Transformers

Because of the high currents involved, power transformers should be located as close to the welders as possible, keeping the secondary bus and feeder runs short. In many cases it will be found advantageous to use transformers containing a liquid that will not burn rather than oil in order that they can be located adjacent to the welding machines rather than at some relatively remote outdoor or vault location. With the load power factor generally falling between 20% and 40%, it is essential that the reactance of the power supply system be kept at a minimum. Generous copper cross-section in welding feeders is usually less important than proper spacing and arrangement of the conductors for minimum reactance.

The supply to the welders should be such that the maximum voltage fluctuation or dip, measured at the last point on the welder bus or distribution wiring which is common to two or more machines, does not exceed 10 to 15%. (This value of 10 to 15% applies to the welding circuit and is not to be confused with the usual limitation of 1 to 2% for lighting circuits affected by the welding load.) It is highly desirable to provide a system which will keep the voltage fluctuation within the 10% limit if consistently good welds without an excessive number of rejects are to be expected. In extreme cases the 15% limit might prove satisfactory, and there are, conversely, some few applications in which the 10% limit might be excessive.

The nominal base voltage may vary gradually from time to time throughout the day due to general plant load changes and other factors, and no attempt is made here to specify an allowable range for this gradual shifting of the base voltage. Obviously, if the gradual change is appreciable from, say, the day operating shift to the night operating shift, it might become necessary during such periods to change the heat or tap setting on all welding machines to compensate for the changed voltage conditions.

Voltage Drop

For convenience the supply system can be broken up into three parts:

1. High-voltage power supply system (2400 volts or higher).

2. Stepdown transformer bank.
3. Low-voltage bus or feeder (240 or 480 volts).

Just how much of the total allowable 10 to 15% drop can be allowed in each of these three parts of the supply system is usually a matter of economics. If the plant is located with respect to the power company's system such that the high-voltage drop is only 1% or 2%, then correspondingly greater drops can be allowed in the transformer bank and low-voltage bus or feeder. Also the relative costs of transformer capacity versus bus capacity is a determining factor in the design of this part of the supply system.

Chapter 8 includes the necessary tables and charts for calculating transformer and bus regulation and shows how to design a plant distribution system for serving welders.

For more detailed information as to power supply for welding operations reference may be made to the literature of the appended bibliography.

NAMEPLATE DATA FOR COMPLETE WELDING MACHINES

Users of resistance-welding equipment have experienced considerable difficulty in the past in their efforts to install adequate power facilities for their resistance-welding machines. This difficulty has been due, in a large measure, to lack of specific information concerning the actual meaning of the nameplate kva. rating of the welding machine. Manufacturers of equipment unfortunately had not standardized on a basis for rating resistance-welding machines and considerable variation might exist even between ratings of any one manufacturer. Through the combined efforts of the Resistance Welder Manufacturers' Association, the American Institute of Electrical Engineers and the AMERICAN WELDING SOCIETY, this major difficulty has been eliminated by a complete standardization of resistance-welding machine ratings and the following nameplate data will appear on each machine:

1. Manufacturer's name and address.
2. Machine number.
3. Type.
4. Transformer serial number.
5. Kva. (50% duty cycle).
6. Voltage and frequency.
7. Maximum open-circuit secondary voltage.
8. Minimum open-circuit secondary voltage.
9. Short-circuit secondary current at maximum secondary voltage and specified throat and gap dimensions.
10. Minimum recommended pressure of water supply.
11. Maximum recommended temperature of water supply.

From the above essential nameplate data, the following additional information can be readily calculated:

(*a*) Transformer turn ratio = maximum open-circuit secondary voltage (7) divided by rated primary voltage (6).

(*b*) Maximum kva. input at rated voltage, (neglecting exciting current) = short-circuit secondary current (9) multiplied by maximum open-circuit secondary voltage (7).

(*c*) Maximum primary-current demand, (neglecting exciting current) = short-circuit secondary current (9) divided by transformer turn ratio (a).

WELDING CURRENT OUTPUT AND IMPEDANCE OF STANDARD EQUIPMENT

As has been stated, resistance welding consists of the heating caused by the flow of current through the parts to be welded. The amount of heating or weld depends, electrically, on three (3) factors:

1. The amount of current (*I*) flowing through the point of weld.
2. The electrical resistance (*R*) offered through the point of weld.
3. The time (*T*) that the current is flowing.

The above factors combined are proportional to, $H = I^2RT$, (see page 270).

A resistance-welding machine must be able to deliver large amounts of current to the point of weld, but, due to the impedance factors, the amount of welding current is only one factor in determining the kva. size of the welding transformer used with the machine.

The path of the welding current through the transformer, arms, electrodes and the work itself is reactive and this reactance and the resistance together offer an impedance to the flow of the current, with the reactive component predominating to give a low-power factor circuit.

Fundamentally, when an alternating electric current is connected to a suitable transformer (primary) winding, an alternating electric current of the same frequency is induced in the secondary winding. The open circuit—i.e., no-load voltage of the secondary is approximately equal to the primary voltage divided by the ratio of the number of primary turns to secondary turns. For example, if the line voltage is 440 volts—and the full primary winding of, say, 100 turns (tap 1) is connected—and the secondary consists of a single turn—then the secondary voltage will be 4.4 volts. If the regulator is moved to point 6 and it contains, say, 50 turns, then the secondary voltage will be 8.8 volts.

Secondary Circuit Calculations

Now, considering the secondary circuit of the machine only, Ohm's law states: $I = E/Z$, where E is the voltage, I the current and Z the impedance—which simply means the restriction to the flow of current, and comprises the resistance and reactance of the secondary circuit and the work. Assume Z to be 0.00044 ohm, then the secondary current with 4.4 volts impressed will amount to 10,000 amp. If the regulator is moved to point 6, the secondary voltage becomes 8.8, and the secondary current 20,000 amp. Thus, the secondary or welding current is controlled by the voltage regulator.

Now the primary current is equal to the secondary current divided by the turn ratio. In the first case 100 turns were used to deliver 10,000 amp.; therefore, the primary current would be 100 amp., and in the second case

of 20,000 amp. the primary current is 400 amp. From the above, it may be seen that the secondary current is proportional to the secondary voltage, and the primary current is proportional to the square of the secondary voltage. In all of the above, the transformer exciting current (which usually does not exceed 5% of nameplate current rating) has been neglected.

Impedance and Kva.

The area surrounded by the machine throat largely determines the impedance of the secondary circuit; the more area the larger the impedance.

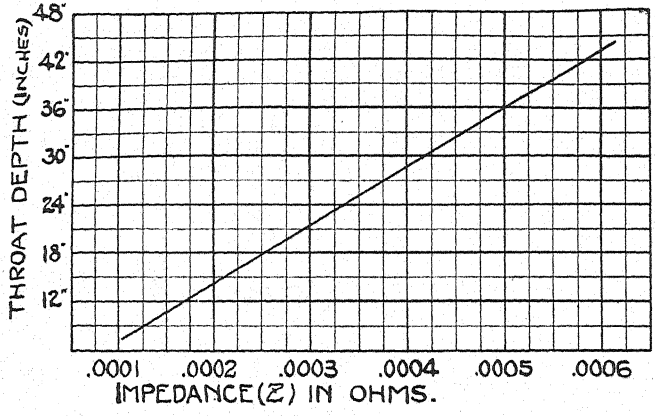


Fig. 2—Illustrating Increase of Impedance with the Throat Depth Increase in a Standard Spot Welder

Figure 2 illustrates the increase of impedance with the throat depth increase in a standard spot welder.

The kva. necessary to produce a welding current of 40,000 amp. at the welding tips of this same machine is shown in Fig. 3.

From these curves, it will be noted that the welding current desired of a resistance-welding machine and the secondary impedance of the machine are both necessary in calculating the kva. necessary to produce that current. The values given in these curves are for only one particular size of machine.

Resistance and Impedance from the Work

No mention has been made of the resistance of the materials to be welded, which in some cases may have an effect upon the calculation or determination of the current output of the equipment.

The extending of the work into the machine throat does, however, affect the output. For example, in the welding of steel sheets, with the work extending a considerable distance into the machine throat, the reactance and consequently the impedance of the circuit will be increased and less current will be available for welding at the points, with the same secondary voltage.

Duty Cycle and Kva. Rating

Resistance welding is done in such a short time (spot and projection welding) that this time necessarily enters into consideration in determining the kva. available with a given kva. nameplate reading.

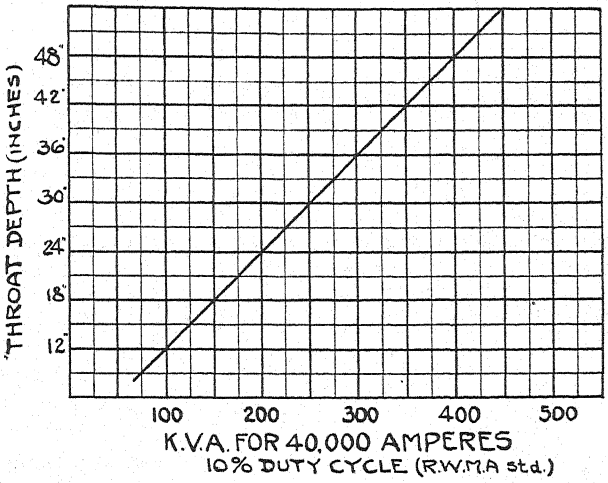


Fig. 3—Illustrating Necessary Kva. to Produce a Welding Current of 40,000 Amp. at the Welding Tips of a Standard Spot Welder

The nameplate kva. rating of a resistance-welding machine is based upon the electrical load-carrying capacity of the machine and its transformer and is not necessarily the maximum kva. output. The R.W.M.A. Transformer Specifications state: "The rating of resistance-welding transformers shall be based on the transformer not exceeding the specified temperature rise for the class of insulation used, when operating on the kva. load appearing on its nameplate on a duty cycle of 50%—when maximum period 'on' is one minute." In the case cited above under paragraph "Impedance," the maximum kva. drawn from the line is (440 × 400) 176,000 va., or 176 kva. The duty cycle is the percentage of time the machine or transformer is in operation. For instance, if the above transformer is in a spot welder, making 100 spots per minute and if each spot is timed at 6 cycles ($^1/_{10}$ sec. on a 60-cycle system) the total "on" time or conduction will be $^1/_{10} \times 100$ equals 10 sec. per min. or a duty cycle of 16.7%. The required rated capacity of a welding transformer is equal to the maximum demand times the square root of the duty cycle times the square root of 2. Thus, in the above case where the maximum demand is 176 kva., duty cycle 16.7%, the required transformer size is: $176 \times \sqrt{0.167} \times \sqrt{2} = 101$ kva. If the duty cycle were 5%, then by the same formula 55 kva. in rated capacity would be required.

Welding Heat

Since the energy of a weld is directly proportional to the current squared,

the resistance of the contact between the piece of work and the time during which the welding current is allowed to flow, each of these three factors must be accurately controlled. In a brief synopsis of this type, it is impossible to go into detail regarding these, but their importance in spot welding should never be minimized.

Figure 2 (Chapter 9) shows the fundamental diagram of spot welding, while Fig. 3 (Chapter 9) shows the thermal gradient chart showing the heat at the different points between the electrodes. This heat is due to the resistance of these different points since the same current flows through all points in a given period of time. This heat condition varies with the electrode diameter, thickness of stock and kind of material. In other words, in spot welding the heat at point *A* (Fig. 4, Chapter 9) is considerably greater for a given material and thickness than it would be in projection welding, due to the fact that the area of contact required for spot welding is less than the area of contact required for projection welding.

The weldability of materials is broadly based on the electrical and thermal conductivity, with some consideration to the melting point. Nearly all the principal metals can be welded, although some materials are considerably more difficult than others. Some, such as lead and tin, are difficult to the extent that it is considered commercially impractical to spot weld them.

Actual impedance values taken in the final testing of standard machines where this factor was an important item in the machine design and construction are given in Fig. 4.

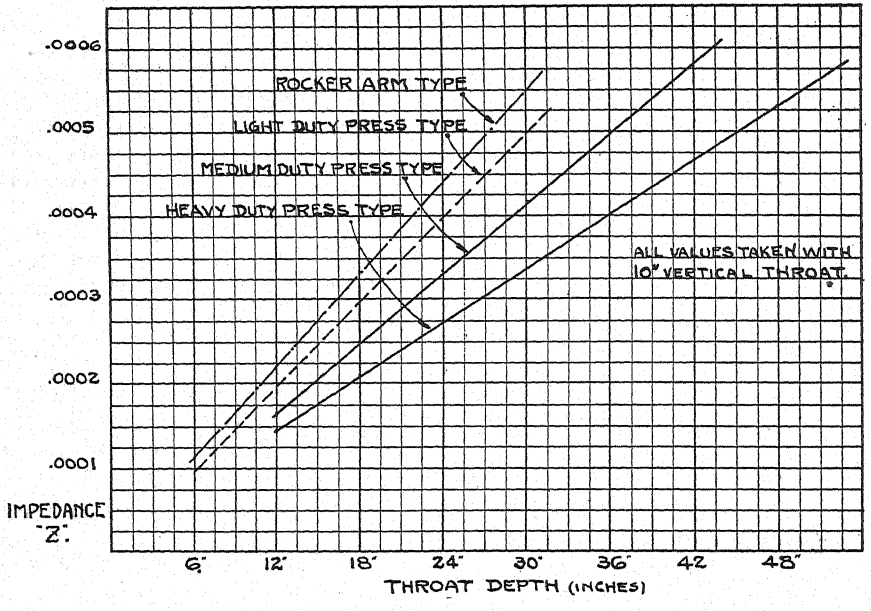


Fig. 4—Actual Impedance Values Taken in Final Testing of Standard Machines

Conclusion

From the foregoing we see that the welding capacity of a resistance-welding machine depends upon the following factors, taking for granted that the input power supply is suitable in all respects:

1. The kva. (at 50% duty cycle) rating of the machine.
2. The throat area and cross-section (determining secondary impedance).
3. The material to be welded determining the current needed.
4. The work or fixtures as they may extend into the machine throat when welding.
5. The duty cycle of heating, to determine the safe available kva. from a given machine.

While the above mostly refers to spot and projection welders, the same circuits and calculations thereof apply to seam, flash and butt welders.

Once the impedance of the circuit is known and standard formulas are available for its calculation (see Chapter 11), the secondary output of the welder circuit can quickly be determined as follows:

$$I = \frac{E}{Z} \tag{1}$$

$$I^2 = \frac{\text{Kva.}}{Z} \times 1000 \tag{2}$$

$$\text{Kva.} = \frac{I^2 Z}{1000} \tag{3}$$

where I = secondary amperes.
E = secondary voltage.
Z = secondary impedance in ohms.

JIGS AND FIXTURES FOR STANDARD EQUIPMENT

Jigs and fixtures are used on resistance-welding machines covering the entire field of resistance-welding applications—spot welding, projection welding, butt and flash welding, seam or line welding—and also applications not directly welding operations, but done on standard resistance-welding equipment such as heating and heading over rivets, preheating for various die or assembly operations and soldering and brazing. (See also Chapter 32C.)

The main object of using jigs and fixtures is identical to that in their use for drilling, milling and other machine-tool operations; to reduce the cost of welding by obtaining greater production, greater accuracy, permitting the employment of unskilled labor and many times saving the cost of a special machine.

The modern automobile, refrigerator, household appliances, furniture, etc., would not be possible were it not for the mass production of interchangeable parts on resistance-welding machines made possible by the use of jigs and fixtures.

To define a jig and fixture we shall call a "fixture" a work-holding and

locating device that is bolted or fastened to a standard welder, being a part of the complete machine. A "jig" will be considered an appliance for holding and locating the work but separate from the welder, either loaded and fed to the machine, or stationary and the welder brought to the work, such as a portable spot-welding application.

The resistance-welding machines used in conjunction with jigs and fixtures are the standard machines as described in Chapter 8. All of these machines readily lend themselves to the application of jigs and fixtures, dial and hopper feeds and automatic conveyor assembly lines.

Methods of Welding

Before a fixture or jig can be designed for or applied to a job, the best possible method of welding the parts must be determined. An operation being done by a repeated single spot-welded method may, by a simple change in the parts, be done by the projection-welding method where all spots to be welded on the parts can be welded by one stroke of the machine, making for higher production and better looking finished piece of work. By changing from the slow butt weld to the flash weld less finishing may be required, or a short seam weld on a difficult shape by the use of a mandrel and roller electrode may replace several spot-welding operations, using a number of different shaped electrodes. It is always best to thoroughly try various methods of welding the parts before a costly jig or fixture is designed and built. The machine available must be suitable for the stock to be welded in kva. capacity and welding pressure. The speed of operation must also be considered.

Welding data are available for the thickness of stock or number of projections that can be welded by the various methods according to the kva. rating of the machine. However, if the machine available is to be speeded up for a faster operation than that for which it was originally built, its kva. rating must accordingly be increased, or the maintenance of the welder, through replacement of parts and particularly the electrical portions thereof, will more than offset the supposed savings for faster operation through jigs or fixtures, due to the consequent overloading of the machine. Series welding, multi-spot welding and indirect welding are described under a separate heading later in this chapter.

Materials for Jigs and Fixtures

The correct use of such materials as tungsten copper or its equivalent, the several grades of alloy copper, aluminum bronze, aluminum and aluminum alloys and non-magnetic cast iron, also insulation materials in their different grades and methods of insulating for protection from electrical current primarily, but also to resist flash particles thrown off the stock when welding; water, dirt and handling protection cannot be fully described here. There are, however, these data available and the designer should be familiar with these materials and use them in their proper places.

Aluminum bronze, or its equivalent, is used for fixture bases, arms clamping devices, stops and such parts of a jig or fixture close to or part of an electrical conductor where greater strength or wear is necessary than could be obtained if brass or copper or other non-ferrous, non-magnetic materials were used.

Aluminum and its alloys can be used extensively in jigs where a minimum of weight is necessary. However, aluminum should not be used for actual current-carrying parts inasmuch as oxidation will develop in time at the joint or clamp of an aluminum conductor for welding currents and sometimes causes serious trouble.

Non-magnetic cast iron is used frequently for parts of a jig or fixture close to or in the magnetic field of the welder. It is cheaper than aluminum or bronze and slightly stronger than ordinary cast iron. Fixture bases, frames and machine arms are frequently made of this material, sometimes known as "nickel iron."

Copper is mentioned last since it is the most familiar and is used as a basis for welding jigs and fixture materials. It occupies as important a place for welding machine jigs and fixtures as iron and steel do for other machine tool operations. Rolled copper in flats and rounds, cast copper and hammered or forged copper are indispensable. Copper, stainless or seamless steel high-strength annealed tubing cast into copper castings should be used wherever possible for water cooling inasmuch as drilled holes in copper castings usually permit leakage of water that is very difficult to stop.

Changes to a Standard Machine

Frequently it is necessary to alter the welding machine in some way to better adapt a jig or fixture for the method of welding desired.

"Rocker arm" spot welders can be easily changed to do a small butt-welding job by replacing the electrodes with simple clamps to hold the work. They can be made to do a short seam-welding job by attaching a roll or roll segment in place of the upper or lower electrode or both. They cannot, however, be altered to do a satisfactory flash-welding or projection-welding job as the mechanical construction of the machine is not suitable.

Motor-driven, air- or hydraulically-operated press type welders can readily be changed to do projection or spot welding by simply altering their electrodes.

It is essential that all projection-welding electrodes be located directly on the center line of pressure application, and that the lower arm be of a sturdy construction to avoid deflection. Press type welders cannot be readily converted to do flash welding or seam welding.

Butt and flash welders are readily interchangeable for either operation. Such change is accomplished more through the method of operating than in actual change of the machine structure or controls.

Standard seam welders can readily be changed for straight and circular seams. They cannot be readily changed to do any other type of welding. Changes to seam welders consist mostly in their adaptation to different sizes of work and usually this means only a change in the lower arm and work guiding device.

Rules of Welding Fixture or Jig Design

Before going into a detailed description of some jigs and fixtures, several rules to be followed in their design and construction will be briefly outlined.

RULE 1—Keep All Magnetic Materials (Iron and Steel) Out of the "Loop."—By "loop" is meant, in a spot welder, the gap surrounded by the upper and lower arm, the electrodes and the base of the machine housing the transformer. This gap is an intense magnetic field and any iron or steel placed therein will attract the magnetic lines and become hot, and in some cases actually melts. The presence of iron or steel in the "loop" chokes the available welding or heating current back from the electrodes, making for poor efficiency of the welder. All parts placed in this "loop" or space must be non-magnetic.

RULE 2—Keep This Loop or Space Described Above as Small as Possible.—This space, sometimes called throat gap, is the cause of many disappointing results in setting up and installing fixtures, for many times a 24-in. or a longer throat machine is used where a 12-in. or even smaller throat machine could be used to much better advantage. Also over-all height of welding fixtures should be reduced to a minimum. All this again makes for more welder efficiency and makes possible the doing of jobs that may seem too heavy for the machine, eliminating excessive losses due to increased reactance and lowered power factor of the machine.

RULE 3—Make All Welding Electrodes Easily and Quickly Replaceable and Water Cool Them as Close to the Tip as Possible.—In almost every case of spot welding fixtures standard electrode tips can be used. These are readily obtained and inexpensive to replace. The inlet water tube should be not less than $^3/_{16}$-in. to $^3/_8$-in. inside diameter, depending on the job.

RULE 4—Insulate All Gage Pins, Clamps, Locators, Index Pins, etc.—In all jigs or fixtures where locating pins touch the work they must be insulated from the current-carrying plate or fixture base by being pressed into a fiber, bakelite or other insulating material sleeve having projection shoulders which in turn are pressed into the base of the fixture. When a gage pin or stop touches both pieces of work being welded, it should be easily replaceable, for electric current shunting across the pin has no respect for the hardest of alloy steel and will pit and burn it, and replacement should be easily made. Some fair results have been obtained in plating (chrome) such locating pins to prolong their life.

RULE 5—Provide Sufficient Cross-Section to Current-Carrying Members and Run as Close to the Electrodes as Possible. Use as Few Breaks or Connections in the Circuit as Possible.—When we consider the characteristics of a welding current, we immediately see the necessity for this. A welding current is extremely high in ampere capacity and carries from 3 to 20 volts, depending on the machine and the job, and a pure copper conductor can only carry a limited current (amperes) depending upon its material and cross-section. If the conductors are too small in cross-section, an excessive voltage drop and increased resistance will result, and the fixture may be useless unless these conductors can be enlarged. And again if that part of the welding fixture that carries the current be built in numerous sections, the reduced effective current at the weld (losses in passing the current from one section to another) will cause low efficiency of operation and costly service and maintenance charges.

For purposes of estimating cross-sections we recommend the following current densities based upon a 50% duty cycle.

Rolled copper sections will carry up to 1800 amp. per sq. in.

Cast copper sections will carry up to 1500 amp. per sq. in.

Water cooling either of the above will increase its capacity approximately 100%.

Speed of operation (duty cycle) can also be taken into consideration. Low-duty cycle will allow more current to be carried per sq. in. of conductor than a high-duty cycle.

The conductivity of other non-ferrous alloys can be obtained and used provided the section is large enough. Where breaks or connections must be made, the clamping surface must be at least twice the cross-section and the surfaces scraped smooth and parallel, and solidly bolted together.

RULE 6—All Moving Slides, Bearings, Index Pins, Adjusting Screws and Any Accurate Locating Device Should Be Protected from Flash.—This is particularly necessary on flash welders although on spot or projection welding some flashing is bound to occur and when as many as 2000 to 4000 welds are made per hour, flashing can cause considerable trouble by getting across insulated pins, causing a direct electrical short, or into slides, making repairs necessary.

RULE 7—Provide Adjustment for Electrode Wear.—Most electrodes for spot welding are pure copper, and, after a production run, wear down a distance so that the stroke of the welder will no longer maintain a welding pressure contact between the electrodes and the work. They then must be adjusted either by raising the entire lower arm or fixture or replacing with refaced or new electrodes. Not only must adjustment of electrodes be provided to maintain a constant welding pressure on the work at all times but stops, gage points, pins, etc., must also compensate or be of a large enough surface to gage the work at both the new and worn-out electrode height.

RULE 8—Check Welding Pressure Application.—Since the welding pressure application to a piece of work has a direct effect on the weld, the design of a fixture must take into consideration the following: (*a*) accuracy in the machine work for projection welding fixtures and electrodes, and (*b*) the elimination of deflection due to the welding pressure, so that the upper and lower electrodes are parallel with each other in all directions and remain so when final welding pressure is applied. When necessary to projection weld at a slight angle the projection should be elongated in the direction of the possible "slide" that occurs when "squeezing" for the weld. Flash-welding clamps must be so designed as to clamp the piece of work with at least twice the final pushup pressure to prevent possible slippage of work and to insure a good electrical contact. The welding height or point where the electrode touches the work in "rocker arm" machines should be in a direct horizontal line to the fulcrum point of the arm, so no slipping or wiping of the electrodes on the work will result when pressure is applied.

RULE 9—Ease of Operation and Protection for Operator.—As is common to all jigs and fixtures for any machine, ease in loading and unloading must be taken into consideration. One feature of a welding fixture that is not common to fixtures for other machines is that a welding fixture must be designed and built to accommodate the loading of usually two or more separate parts that become, after the welding operation, only one piece that

must be unloaded. Care must be taken that a welding fixture or jig will unload properly when the parts are welded. The danger to the operator when loading and unloading fixtures and jigs, from the standpoint of electrical shock, is very remote provided there is no primary short in the machine. The secondary current, or welding current, is of very low voltage and is entirely safe even though the secondary circuit is unprotected. However, for the operator's protection only one side of the secondary circuit—either above the top electrode arm or below the fixture base—should be insulated from the base of the machine. The welding machine should also be grounded so that, if a primary short develops in the transformer or controls, it will be positively grounded through the welding machine and not through the operator, as would be the case if both sides of the secondary circuit were insulated from the machine base and the operator was touching both upper and lower electrodes or electrode supports. Further protection for the operator's hand should be taken into consideration by providing guards on hand-loaded electrode dies. The use of two hand-operated control switches that must be pressed by the operator's two hands usually is a simple method of absolute safety.

RULE 10—Be Sure the Fixture or Jig Is Suited to the Job and the Machine.—As stated in a former paragraph, all phases of possible welding operations should be considered as well as the machine to be used and the number and size of pieces to be welded. All have a direct bearing on the type of fixture used. When the method of welding is determined, time should be taken to completely check the parts to be welded so as to provide for sufficient electrode surface and clearance. Be sure that the welds are in the best possible position, that the stock specified is weldable, that necessary provisions are made for clamping and gaging, that allowances for flash-off are included and that the correct size and shape of projections, or correct amount of lap, are used.

To determine the above several sample welds should be made, either on the machine to be used with the fixture or jig, or a similar machine, from which sufficient data can be obtained to specify the machine required. Allowances should be made, of course, for the new arrangement and speed of welding.

Welded samples of the job should always be made, whenever possible, and thoroughly tested before the design or construction of a fixture or jig is started.

RULE 11—Provide Sufficient Water Cooling.—This very important rule is usually very much neglected and brought forcibly to attention through overheating, excessive electrode wear, transformer burnouts, etc.

On a high-production job where electrodes are welding with each stroke of the machine, running continuously, an individual and separate water-cooling line should be provided for each electrode. A sight drain pot should be provided and inspected frequently to insure a flow of cool water. Regulating valves should be provided to adjust this water flow to prevent waste. Various types of water cooling should be considered. The flood system of a constant external flow of water into a drain pan is very efficient, particularly for seam or line welding. Water cooling through troughs cast in the sides of the fixture support provides much more water-cooled surface than a drilled hole. Cast-in pipe or tubes in copper castings should be

used where various angles or bends of the cooling paths are necessary. In the case of small jigs to be handled frequently, there should be several provided so they will be used at adequate time intervals to allow them to cool sufficiently between welds to permit handling. Welding completely under water is always possible but care should be taken to provide a suitable water container to prevent water splashing over on the operator or floor. Also make sure that the work and water are clean, preventing dirt or foreign matter from being carried into the jig or fixture and clogging up the faces of the electrodes or contact surfaces. Welding under water has been found a decided advantage in seam or line welding of small diameters where sufficient water cooling could not be provided in the lower arm because of work clearance. Also in the dial feeds for projection welding, that method has simplified the water circuits considerably.

RULE 12—Knockouts or Strippers.—In a welding fixture or jig for heavy welding when the stock may not always be clean, there is a tendency for the work to stick to the electrode faces. This should be taken into consideration where progressive jigs are used, also when automatic or quick loading and unloading of the work is desired. Knockout pins, operated through a leverage advantage or by an air cylinder, or a positive stripper save considerable production time and add to the operator's protection.

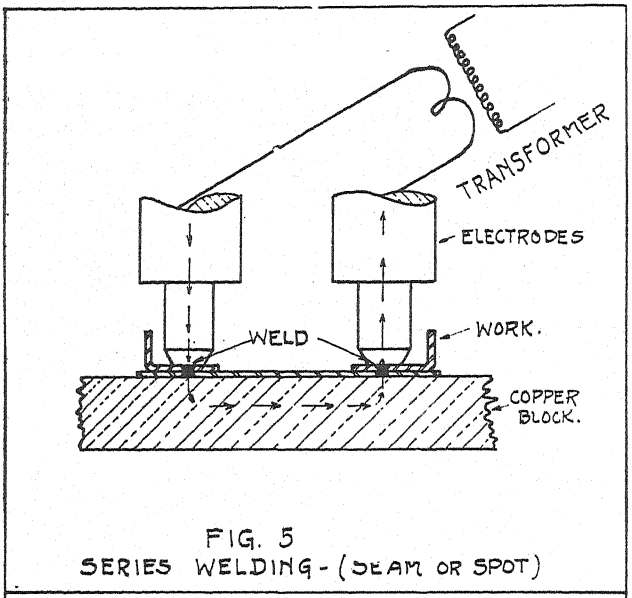
RULE 13—Stationary Parts of the Fixture and Work Affected by Magnetic Field of Machine.—The magnetic pull of a welding machine toward the transformer is frequently of such intensity as to lift small pieces of work out of their locators, and small eccentric clamps made of steel, when sufficiently close to the loop to be affected, are sometimes actually released by this force. Work holding plates and clamp handles of non-magnetic material will prevent this condition.

Series, Multiple and Indirect Welding

The above are general rules applying to most fixtures for resistance welding. It would be impossible to cover in detail the design and operation of flash-welding clamps and fixtures, projection-welding fixtures and locators, etc., as each and every job has its own characteristics and application. There are, however, several problems that would result in a ready solution if the less familiar methods of welding were better known. We refer to Series Welding, Indirect Welding and Multiple Spot Welding, any of which methods can be applied to a standard welding machine, or at least to a fixture designed with one of the above methods in mind.

The "Series Method" of resistance welding is applicable to spot, projection or seam welding, and is illustrated in Fig. 5. Its application in spot or seam welding is especially desirable whenever possible. Its advantages are: (1) welding two welds in a piece of work at one machine stroke, or (2) welding two pieces of work where it is essential that no markings, indentations or discoloration occur, on one side of the finished assembly, (3) welding with all pressure application on one side of the work, such as large tanks and bodies where otherwise an extremely long throat depth would be required. The welds must, however, be far enough apart to insure the welding current passing through the lower conductor bar instead of the work. Usually

Fig. 5—Illustrating Principle of Series Welding (Seam or Spot)



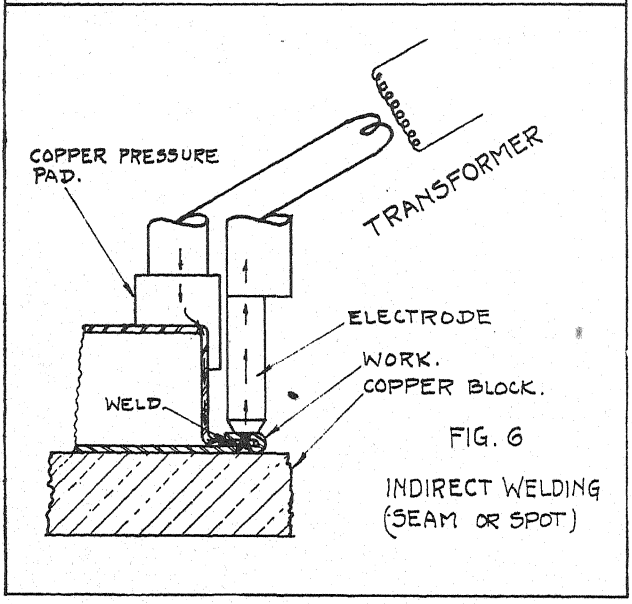


Fig. 6—Illustrating Principle of Indirect Welding (Seam or Spot)

1 or 2 in. is a safe minimum to consider on very light gage material whereas from 6 to 8 in. will be found necessary on heavier gage material.

The "Indirect Method" of welding is usually used where the welding current must pass through the side or ends of a piece of work which, due to its shape or the presence of some subassembly on the part before welding, prevents the welding current from going into the work in the conventional manner. Figure 6 illustrates this method being used.

"Multiple Spot Welding," Fig. 7, shows arrangement for applying multiple spot-welding electrodes to a standard machine. It illustrates the equalized pressure arrangement so necessary for the welding of two or more spots at one time. Applications for any number of multiple electrode assemblies can be used, depending on their spacing, size and capacity of the machine.

Similarity of Welding Jigs and Fixtures to Other Jigs and Fixtures for Other Machine Operations

Clamping arrangements, locating points, general design for quick loading and unloading, weight distribution, etc., all follow along the same lines used for conventional jig and fixture design. Perhaps more in welding than in other machine operations, the operator should, if possible, be able to see the weld as it is being made, since electrode replacement due to wear and necessary changes in heat setting due to voltage fluctuations during the run are required and must be made by the operator.

Auxiliary Electrical Devices for Fixtures

An electrical control circuit is a part of every resistance welder and this electrical circuit can and should be used extensively for the operation of such devices as solenoid valves and clamping devices, magnetic chucks and hold-downs. Simple magnets, built into the welding heads, or electrodes (where spring holding clips are not desirable) many times simplify the handling and locating of small parts, particularly where a small piece is to be welded in the center of a corresponding large piece of work, allowing the small piece to be held and located on the bottom of the upper electrode. The armature in some cases can be a small distance from the piece of work (depending upon its size) and an a.c. coil used at the opposite end. This coil can be connected to the motor starter and be energized continuously while the machine is running, the work being pulled off by the weld or its circuit broken periodically by an auxiliary limit switch.

Solenoid-operated valves for air, water or oil, which in turn actuate feeding or clamping cylinders, operated from pressure or roller limit switches, can produce an entire sequence of difficult clamping and loading operations entirely automatically and can be operated from the main cam or clutch of the motor-driven welder.

Combination of Operations

On many pieces of work the final operation is the resistance-welding operation. This has led to the incorporation of the welder or necessary

parts thereof into special machines, primarily designed for other operations. Tube-rolling machines, assembly machines, turn tables, conveyor sections use a transformer and pressure application of electrodes and a

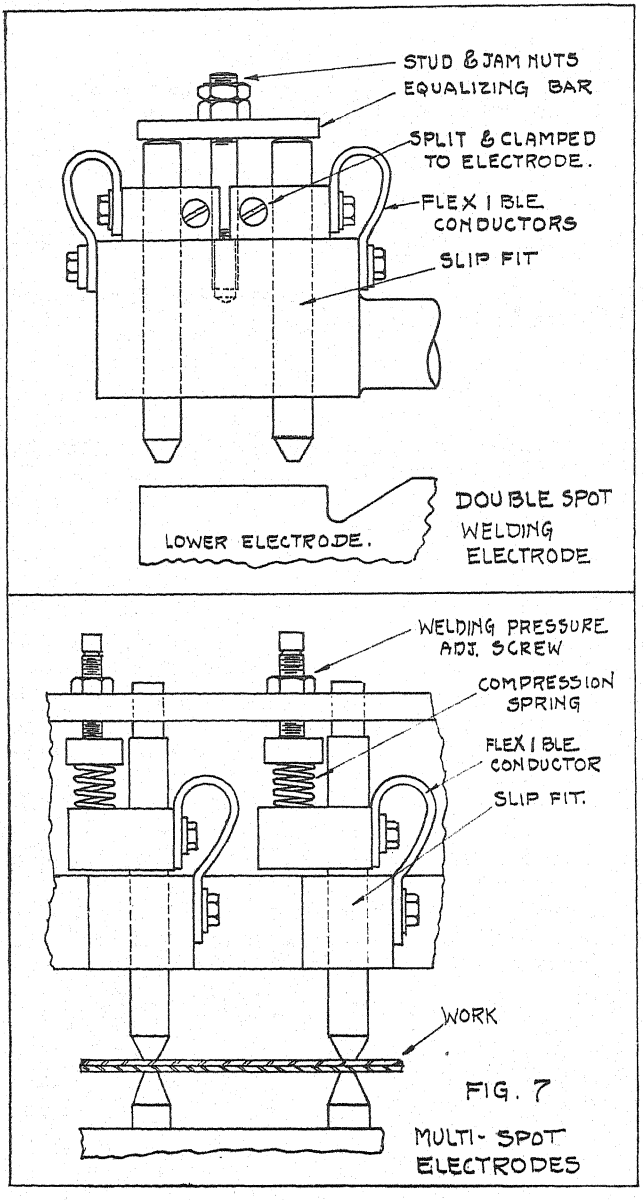


Fig. 7—Illustrating Double Spot-Welding Electrode (Above) and Multispot Electrodes (Below)

control, placing these units at the location desired and synchronizing the operation of welding or heating to suit such requirements.

Combinations such as heating and upsetting, heating and cutting off, welding and annealing, filling a container just prior to welding the head in place are many times incorporated in one welding fixture.

Jig and Fixture Illustrations

Spot-Welding Fixtures.—Figure 8 illustrates a small spot-welding jig for welding together the two parts comprising the base for a fractional hp. motor. This jig locates the parts accurately for welding and also locates the position of the six spot welds required. The work is done on a standard spot welder without any changes to electrodes or arms.

Referring to Fig. 8 the work is shown in detail and the two parts, *A* and *B*, are to be welded by six spots at *C*. The jig is comprised of a base and a hinged top plate. Part *A* is loaded into jig when open and located by placing slots over the four insulated pins *D*. Part *B* is then loaded by placing this part between stops *E*. This jig is then closed and locked by handle *G* and insulated pins *I* hold part in place. The jig is then picked up bodily and placed over lower electrodes which for each spot fits radius *J*. The irregular contour of this hole is in both top and bottom parts of jig. The six welds are then made in sequence and finished work removed from jig.

In many cases for an operation similar to this, two or more jigs are used so a helper can unload and load while an operator welds the parts.

The fixture mounted on a motor-operated, press type spot welder, illustrated by Fig. 9, moves a piece of work under the upper electrode and over the lower electrode for a complete row of spot welds following an irregular contour. Upon each welding stroke of the upper head a ratchet index is actuated. This revolves two cams which transmit the desired motion to a compound slide upon which the work is clamped. Thus, either overlapping spots for a continuous pressure-tight seam of irregular outline or a series of definitely spaced spot welds can be produced automatically.

Two or more standard machines can be used on one piece of work with a locating fixture and support between them. Figure 10 illustrates a spot or projection welding set-up, using two standard motor-operated machines. Spot, seam, flash or butt welders can also be arranged in similar fashion.

Seam Welding Fixtures.—Figure 11 illustrates a two-station, seam-welding fixture for welding two halves for a container as shown in the detail of the work. The lower half is loaded on pin *A* and the upper half directly on top, with flanges together. Handle *B* is then raised and top pin *C* holds the top half in place. Both these locating pins are spring mounted. Hand lever *D* then closes the roller arm *E* to a definite stop and rollers *F* then maintain concentricity of the two halves during the welding operation. The welding rolls and portions of the welding machine are shown in dotted lines. The entire fixture is mounted on a slide and with an adjusting screw can be raised or lowered to compensate for roll wear

The two stations are rotated by hand and through a foot-operated index pin *G* are located in welding position. This foot treadle is also arranged

so that it automatically starts the welding sequence when the index pin locates the station, the welding sequence being the lowering of the upper welding roll which is driven and which in turn revolves the work, completing the seam weld. The operator, then ready for indexing to opposite station,

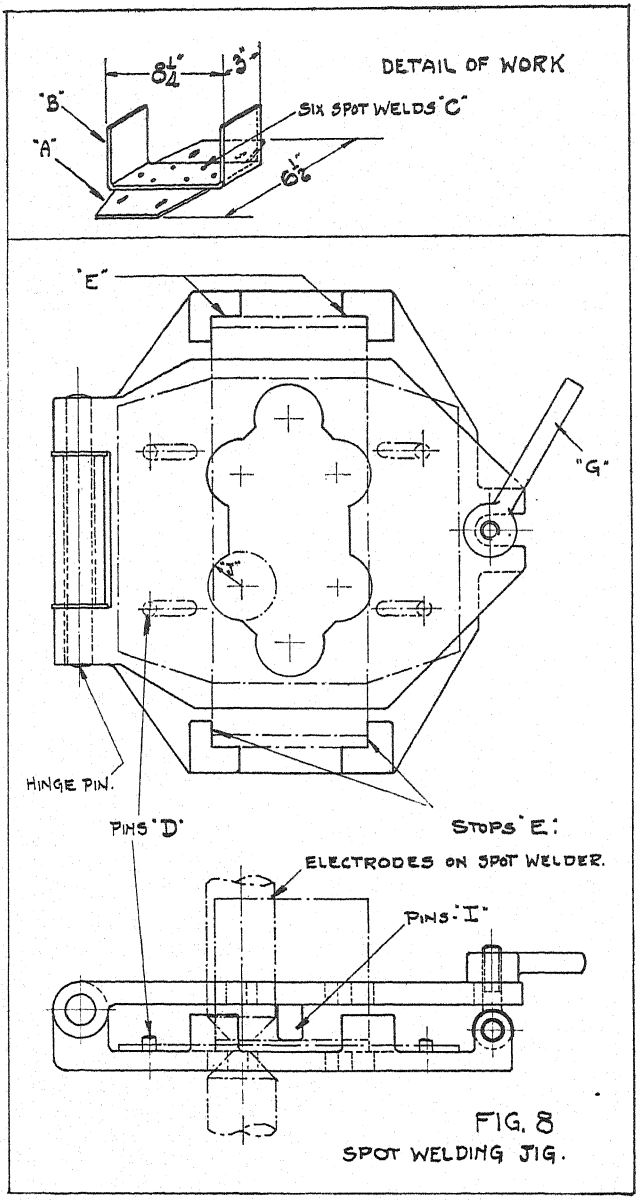


Fig. 8—Illustrating Spot-Welding Jig

presses the foot treadle which breaks welding circuit and raises the upper roll. The above fixture is for mounting on a standard circular seam welder.

Figure 12 shows a work clamping and guiding fixture mounted on a standard straight seam welder.

The work as shown is a cylindrical band and the side seam is to be welded. The work is loaded against the back stop and clamped on both sides of the

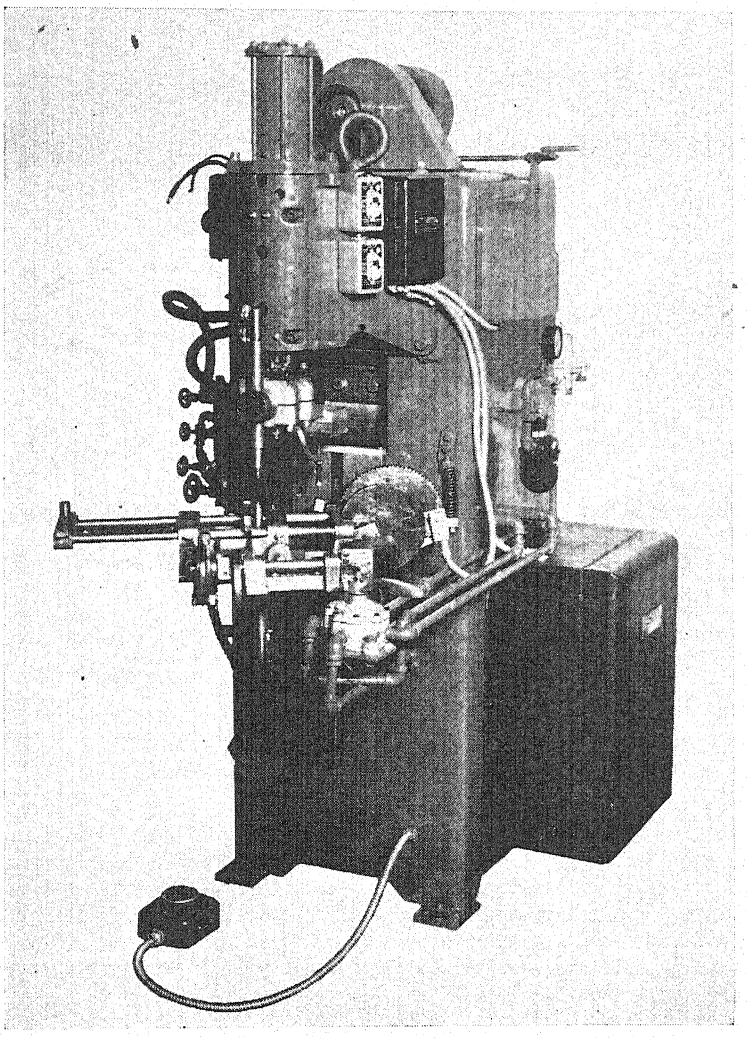


Fig. 9—Special Work Holding and Guiding Fixture Mounted on Motor-Operated Press Type Spot Welder

weld by hand-operated locking clamps, which in turn are mounted on a roller carriage with hollow center for lower welding roll clearance. In operation the work and clamping carriage travel for the length of seam to be welded.

Flash- and Butt-Welding Fixtures.—Figure 13 illustrates a flash-welding fixture for a 3-in. diam. spherical shell. The detail of each half is shown. The usual standard hand-operated flash welder is used and the fixture consists of a left-hand die mounted on the usual stationary platen, a center

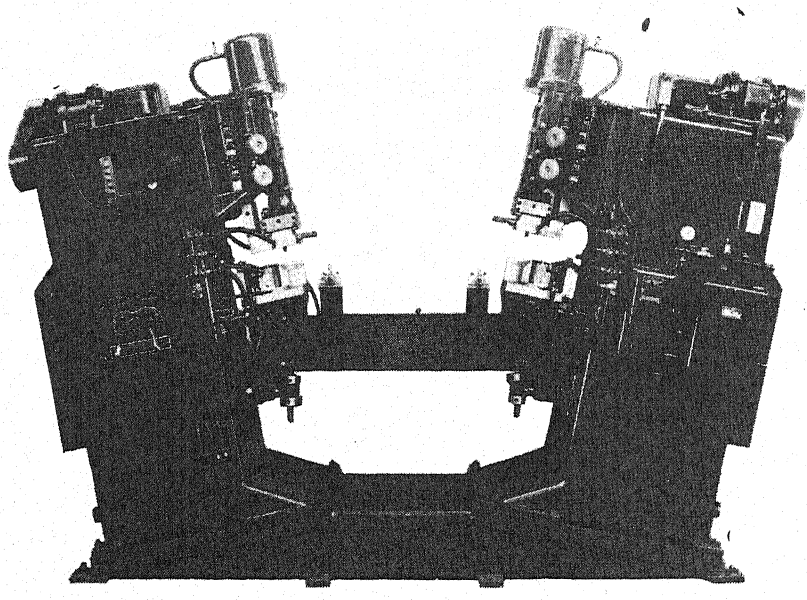


Fig. 10—Two Standard Press Type Projection Welders Tied Together by Special Work Locating and Supporting Fixture

gage for alignment of the two halves and the moving platen die. Both dies are split and hinged completely open for loading and unloading.

After placing the two halves of the work in the dies, the dies are swung shut but are not locked. The handle *A* then moves the left hand die against the center gage *B* (straightening the toggle links), squaring up the work. The handle *E* is then turned 90° and this half is locked through a "T" clamp *F*. The moving platen is then moved against the center gage *B* and when the work in this die is squared up, it is clamped. The center gage is then raised and the two halves flash welded together; then the dies opened and the work removed.

From the above it will be noted that in flash or butt welding the clamp assembly used incorporates the special fixture requirements.

Flat, round or irregular shaped work can thus be located and clamped with clamp assemblies especially designed for the particular work.

Automatic Dial Feeds.—Figure 14 illustrates a cross-section through an eight-station dial. This assembly is mounted on the front of a motor-driven spot or projection welder, and is driven by a shaft extension from the welder clutch box, through a roller chain drive to sprocket (*A*), thence

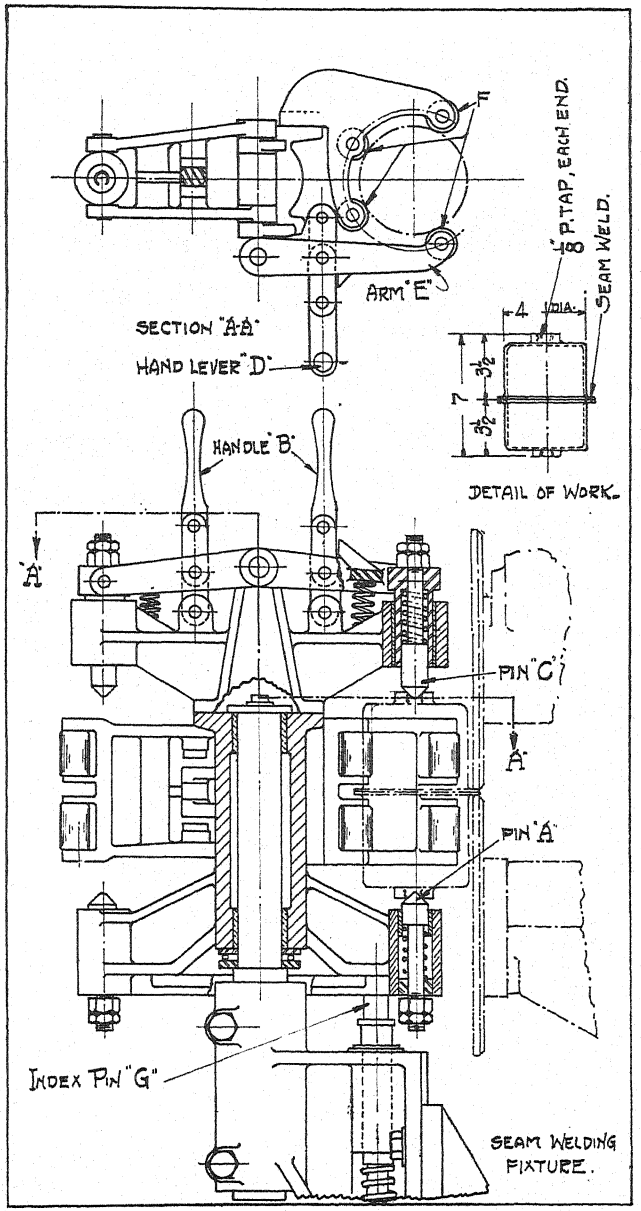


Fig. 11—Two Station Seam-Welding Fixture

through bevel gears *B* and Geneva drive *C*. The main spindle *D* is of copper, and commercial alloy copper is used for bushings and contact plates *E*. One contact plate is fastened to the revolving spindle and one to the lower support casting *F* (also made of copper) by flat head screws.

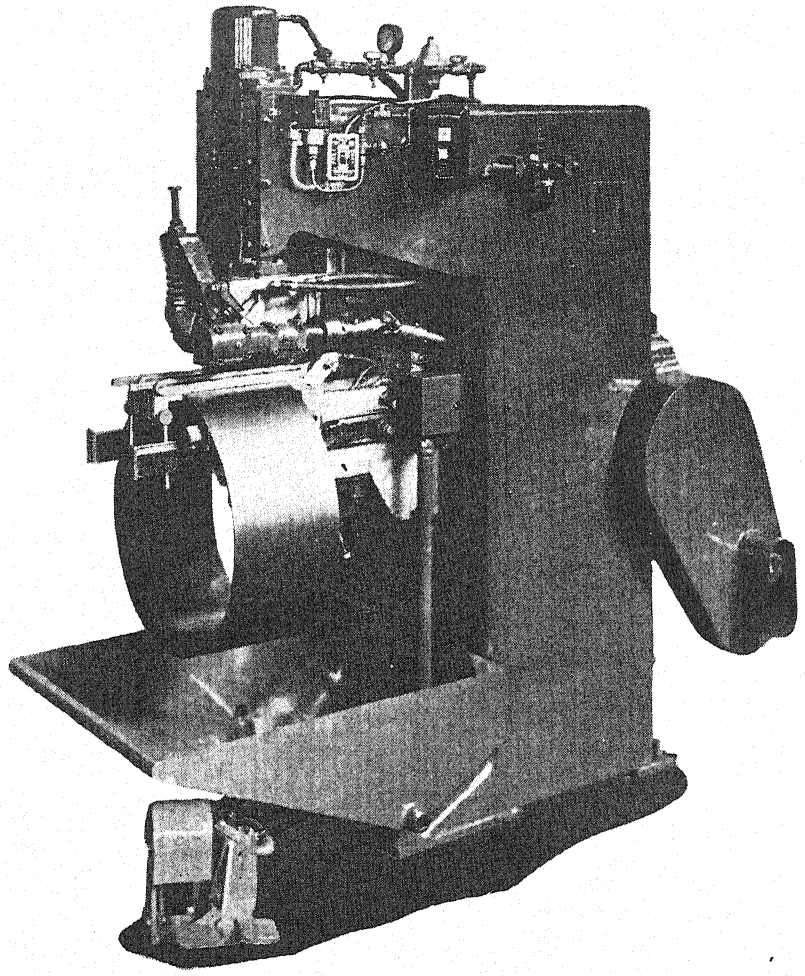


Fig. 12—Special Work Clamping and Guiding Fixture Mounted on Standard Straight Seam Welder

The lower electrodes or dies *G* are simple in construction and wear space is provided. The water connection stuffing box *H* provides for water cooling through inlet *I*, through center tube, around inside of the dial and returns through outlet *J*. The bevel gears and Geneva drive are en-

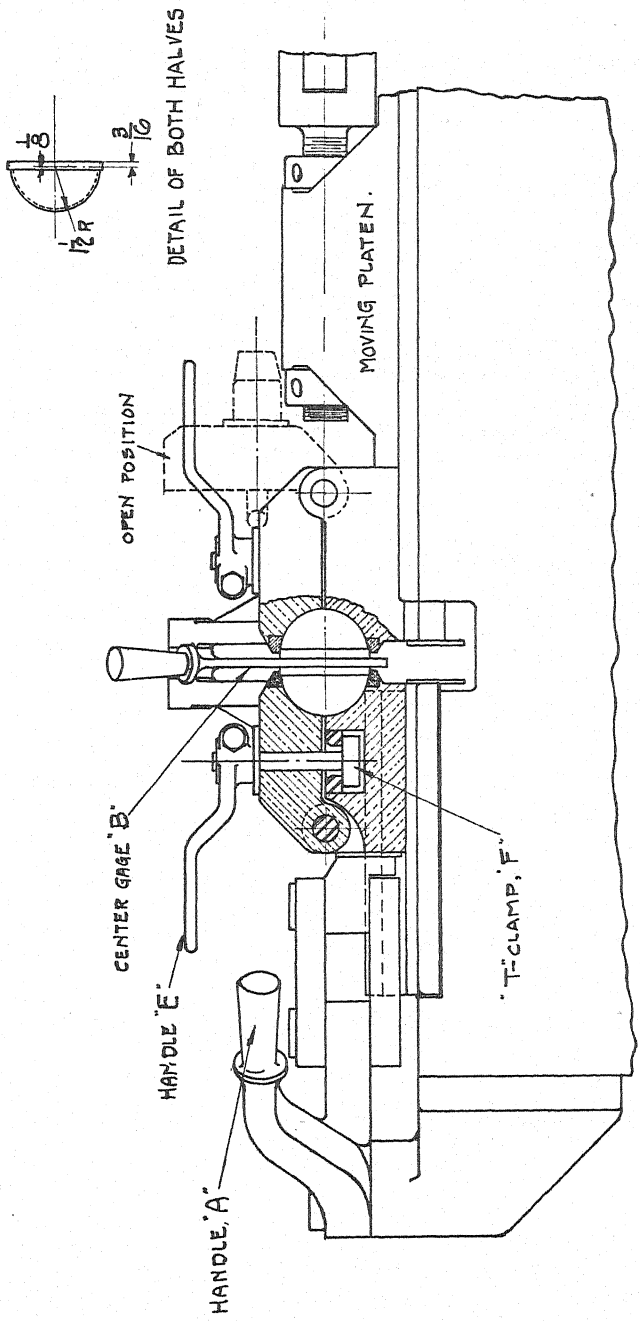


Fig. 13—Special Flash-Welding Fixture

closed and run in oil. The Geneva wheel is both clamped and keyed to the spindle.

Generous lubrication is provided between the contact plates and spindle and bushing. The casting *F* is directly connected to the welding transformer and the welding current passes through this casting into the lower electrodes, through the contact plates *E*, thence through the work to the upper electrode and back to the welding transformer.

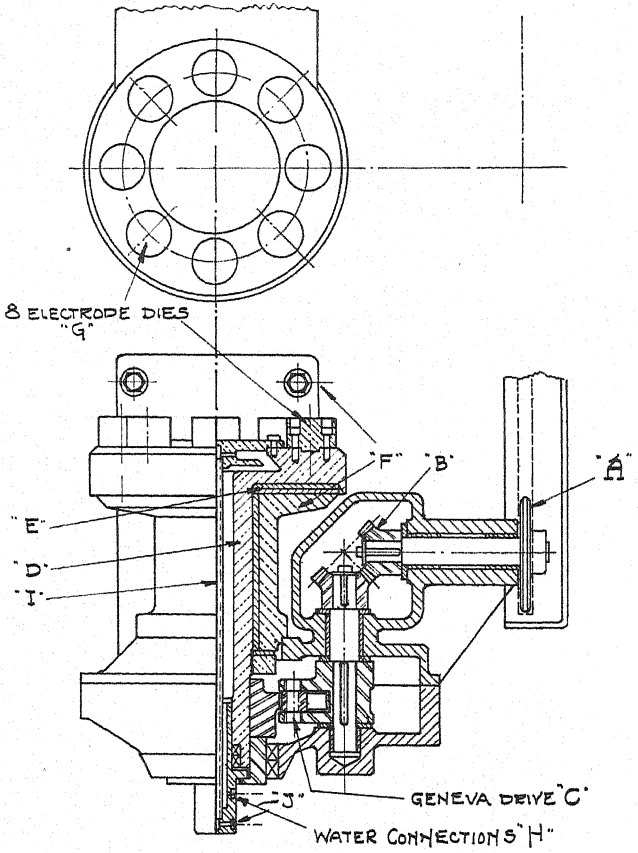


Fig. 14—Cross-Section Through 8-Station Dial Feed Fixture for Press-Welder Application

The dial illustrated is for rather light duty. For heavy-duty welding the same principles apply, except that a more generous water supply should be provided by means of an outer aluminum cover and top plate completely flooding the dial surface with water, and various dial-actuating devices to suit the size of the dial and speed required for the heavy-duty operation should also be provided.

General Fixture Application

The actual application of jigs and fixtures in many cases assumes a more important phase of the welding operation than the welder itself. For the welding of railroad passenger coaches and freight cars, fixtures holding the entire car side or top are used, and all welding done in a single continuous welding cycle over the entire car side or top. Series welding, with carriage-mounted welders, or portable welding guns, or the pry-bar method is used.

Small welding jigs mounted on rollers and having a railway track for moving them from the loading, welding and unloading stations, and even sometimes dipping down into a water trough for cooling are frequently used.

Special collapsible fixtures for the welding of food compartments or inner liners of the modern refrigerator are an example of unique fixture application for seam welding. In this case, the welding splines are inside and welding rolls on the outside of the box. When welded, the box must be unloaded through the door opening, which is always smaller on two and sometimes all four sides than the outside dimension (where the weld occurred). After the weld, the fixture is collapsed (air operated), and the side welding plates assume an unloading angle—without breaking the welding surface of the inside electrode splines. In most cases a series weld is used and the two internal platens are hinged about a pre-located center, thus assuming an unloading angle. One welder is usually provided with a fixture for several sizes of the above, thereby many times exceeding the cost of the welder itself.

Automobile bodies call for close precision in welding fixtures, from the flash welding of the large panel section on some of the largest welders in production to the locating of the clips in the instrument board by the smallest of spot welders.

In the majority of cases, such as flash welding automobile rims, high-speed steel parts to cutters and drills, seam welding small containers, toys and innumerable other articles, the addition of back stops, loading plates, guides, simple automatic trips, locators, etc., at a very small expense can greatly increase the utility of the welder and lower production costs.

Welding jigs and fixtures can be designed and built with any practical degree of close tolerance that is used in any machine tool operation.

PORTABLE WELDERS AND FIXTURES USED WITH PORTABLES

Portable welding tools or welding guns, as generally called, embrace a wide variety of sizes, styles and shapes. Originally developed for welding large parts that were impractical to weld on a stationary welding machine, their adoption has now spread to a wide variety of uses.

The use of portable welding guns is not confined to high-speed production methods. They have a definite place in moderate and low production set-ups, and these guns can be designed and built to accommodate a wide variety of similar or dissimilar work.

Portable welding guns fall into three general classes: pinch guns, expansion guns and bar or lever-type guns. The portable pinch welding gun

is a more versatile tool and can be used either with or without a fixture. The expansion gun and bar-lever gun, however, require a suitable fixture for their use.

Pinch Welding Guns

Pinch welding guns are mechanically, pneumatically or hydraulically operated. However, the mechanically operated pinch gun is rarely used. There is, however, a distinctive place in industry for each of these different types of tools and various pertinent factors will determine the selection of the proper type for the particular job involved.

Standard Gun Types

Portable pinch welding guns are divided into the following classes according to their particular style:

The "C" type gun.

The Scissors or Rocker arm type of gun.

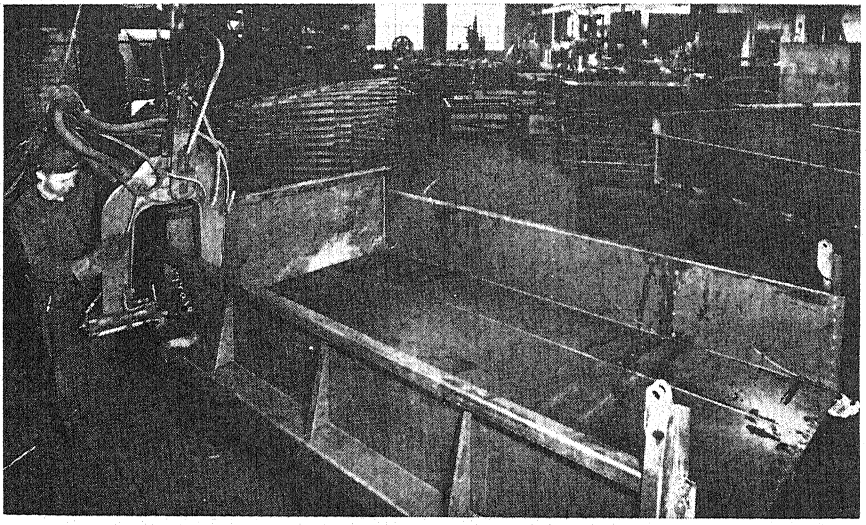


Fig. 15—Clam-Shell Type of Gun—Welding Dump Truck Bodies

The Clam Shell, which is similar to the Scissors gun with the exception that both jaws open to a wide angle which permits entrance or removal over a wide section. The jaws of the welding gun are moved either by mechanical, air or hydraulic medium back to normal relationship to each other preparatory to the actual welding operation itself (Fig. 15).

The revolving jaw type of welding gun is similar in type to the "C" gun with the exception that either one or both jaws can revolve to permit the necessary clearance when positioning the gun for welding.

The "Universal" type of welding gun is a special adaptation of the Scis-

sors type gun. The gun proper rotates 360° on the horizontal axis and approximately 170° on the vertical axis.

Cableless Type Welding Guns

All portable pinch welding guns have two jaws; one of these is called a stationary jaw to which is generally attached the operating mechanism. The other jaw is called the movable jaw. In some classes of guns there is attached to this movable jaw a flexible cable which connects at one side of the transformer secondary. The stationary jaw is also connected to the transformer secondary by a similar cable. In a cableless welding gun, the movable jaw or piston requires no flexible connection as the current is transmitted from the cylinder of the gun directly to the operating

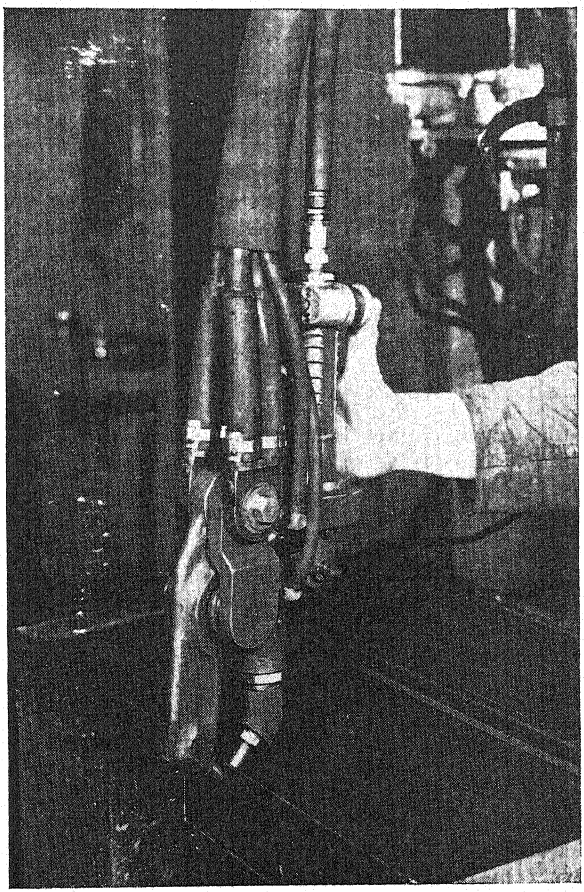


Fig. 16—Fulcrum Pin Cableless Type of Welding Gun

piston of the gun by an offset welding point or an expanding type piston assembly. The cylinder bracket is connected to the stationary jaw generally by means of insulated bolts. Naturally these two jaws are insulated from each other, and both welding cables are connected at this one place by means of a single insulated bolt or hydraulic cable clamp.

The Fulcrum Pin cableless type of welding gun is generally used on a Scissors type of pinch welding gun, eliminating cable movement which itself is the greatest factor of maintenance cost in a portable welding gun (Fig. 16). As the name implies, the fulcrum pin assumes the double function of carrying the necessary welding current to the movable gun jaw and also as the pivot pin of the gun jaws. This is accomplished as follows: The fulcrum pin of a generous size is directly fastened to a short jumper. The jumper is insulated from the stationary jaw, one side of the welding cable assembly is connected to the jumper and the other side of the welding cable is connected to the stationary jaw. Generally, a single insulated bolt is used to effect this connection and, in quite a few cases, the hydraulic cable clamp is used at this point which clamps the jumper and pin when the pressure is being applied to the welding points, but releases them at all other times permitting the rotation of the gun without any movement of the welding cable. The fulcrum pin is insulated from the stationary jaw and the current is conducted as follows: As the gun is operating, the movable jaw swings in an arc around the fulcrum pin. When the welding points come together on the work and the pressure is increased, the fulcrum pin ceases to be the theoretical fulcrum of the gun and the welding tips themselves assume that function. At this time, welding current is passed from the welding cable through the jumper through the fulcrum pin to the movable jaw. No arcing results due to the pressure on the pin at the time the current is passing.

Hydraulic Cable Clamp Type Gun

The hydraulic cable clamp mentioned above is actually a squeezing hydraulic cylinder, the piston of which is essentially a bolt that extends beyond the cylinder proper. This hydraulic cable clamp is used in place of a single bolt to fasten the welding cables to either the cableless type pinch welding gun or the fulcrum pin cableless type pinch welding gun.

The chief advantage of the hydraulic cable clamp is permitting free gun movement without a movement of the welding cable.

Expansion Welding Guns

Expansion welding guns are of two general types, one the short-circuiting type, and the other the single-cable type. These guns should be properly classified as fixture type guns, as a welding fixture is necessary for their operation.

The short-circuiting type gun, as the name implies, merely conducts the current from the upper electrode of the fixture to the lower electrode of the fixture on which the work is placed. Both the top and lower electrode are connected to the welding transformer secondary, the transformer

necessary being an integral part of the fixture. Short-circuiting guns are either air or hydraulically operated and are of the cableless type and also of the flexible shunt type. They are available with the pistol grip type of handle and also extension handle which can be either straight or at an angle to suit the type of work being performed.

The single-cable type of expansion gun is similar in operation to the short-circuiting type, with the exception that the lower electrode of the fixture is energized. The other side of the transformer secondary is connected to the cable which is in turn connected to the welding gun proper. The reason for this type of gun is that of economy. It permits the use of a cheaper fixture. The disadvantage, however, is the fact that the welding condition varies due to the fact that the changing of the position of the gun also results in the changing of the characteristics of the fixture proper due to the varying air gap and the reactance. While this is not of extreme importance, it must, however, be taken into consideration when designing the fixture of this type in order to obtain the necessary good welding results.

Short-Circuiting Pinch Gun

There belongs in this classification of fixture welding guns, the short-circuiting type of pinch welder gun. This gun must also necessarily be used in conjunction with a fixture and the general construction of the fixture is as follows: An electrode fitting the work that is to be welded is connected to one side of the secondary; it is on this conductor that the work is positioned. Immediately below this conductor and insulated from it is another conductor which is connected to the other side of the secondary. Both conductors are supported on a fixture with sufficient room left to allow the entrance of a pinch gun. The current is conducted from the lower conductor through the gun to the work proper.

Bar Guns

Bar or lever type guns are either manually or air or hydraulically operated. They are always used in conjunction with a fixture. The work is positioned on the stationary electrode which is directly connected to the transformer secondary. The other side of the secondary is connected to the copper bar which encircles the work to be welded. The operator inserts the welding gun under the outer electrode and positions the point on the work proper. After applying pressure, manual or otherwise, the welding cycle is initiated by the pressing of a switch on the gun, which is generally connected to the welding contactor. Timing and pressure may be controlled manually or automatically.

This type of gun can also be the straight bar type with a hook incorporated at about the center of the gun. This hook is engaged underneath the outer copper bar and the pressure is applied on the other end of the bar which generally rests on the supporting frame.

This type of gun properly falls into the classification of the short-circuiting type of gun.

PORTABLE WELDER GUN CABLES

Portable welding guns require flexible cables to conduct the secondary welding current from the welding transformer to the gun proper. These welding cables are available in various styles, sizes and classes. There is a great variety of terminals on these individual welding cables, the most common of which are the straight-threaded adapter, the threaded adapter with the union type swivel connection, tapered cable terminals and the flat, single-bolt lug.

Standard Type of Cable

The standard welding cable generally consists of the two cable terminals with the cable proper soldered or brazed to each terminal and the cable covered with a loose-fitting, tough rubber hose that can be either vulcanized or clamped to the terminals proper. The terminals are generally drilled to permit the water to flow through them from the cable assembly, the water flowing between the cable and the cable covering. This type of welding cable is shown in Fig. 17.

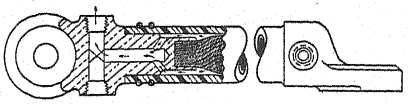


Fig. 17—Standard Portable Welder Cable

Another type of welding cable widely used is that of the hollow core type. In this construction, a loosely crimped hollow copper interlocking core is the center of the cable and the flexible strands or ropes of flexible copper strands are spirally wrapped around the core. The assembly is covered with a closely cotton-woven braid, and this whole unit is covered by a tough vulcanized rubber covering. With this type of cable, terminals are fastened by two methods, one of which is the spinning on and crimping of a specially designed fitting, and the other method is that of a sleeve ferrule which is in turn soldered to a conventional terminal.

Cooling is effected in this cable by means of passage of water through the loose hollow interlocking core. The water flows through the interstices of the core, thus cooling the entire cable. A picture of this cable is shown in Fig. 18.

Low Reactance Type Cable

The low reactance type of welding cable, Fig. 19, consists of two pairs of cables, each pair being connected to a common terminal at each end. These cables are then assembled and wound spirally. The entire assembly is then gum dipped and heat cured. This method of construction reduces the reactance which causes the cables to kick, thus eliminating fatigue and shock to the operator.

The construction of another cable of this type follows the above cable with some refinements, using six individual strands of cable wound in a spiral around a rubber hose. The strands are insulated from each other by means of a formed rubber separator. Every other strand is soldered into one of two end terminals. These two terminals are then insulated and are fastened together with insulated bolts. The tough flexible rubber covering is clamped to each terminal by means of wire clamps.

These assemblies result in a single enclosure but are actually two cables in one. Various sizes and shapes of short jumpers both stationary and flexible are available for the attachment of the gun to the cable to the transformer secondaries.

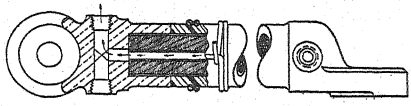


Fig. 18—Hollow Core Type of Portable Welder Cable

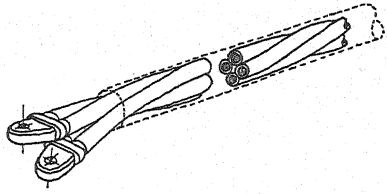


Fig. 19—Low Reactance Type of Portable Welder Cable

The features of this type cable are its flexibility, the reduction of the high reactance of regular single cables and the reduction of shock and fatigue to the operator.

Summary of Welding Cables

The selection of the particular welding cable is quite often a matter of individual preference coupled with the results obtained in the past and with the desire to reduce the amount of items carried in the regular maintenance stock. The proper cooling of the welding cables, which should be individual whenever possible, their proper hanging, clamping and supporting will greatly increase their life.

Cables are generally rated in size as to their circular mil capacity, the most common sizes being 250,000 C.M., 400,000 C.M., 500,000 C.M., 600,000 C.M., 750,000 C.M. and 1,000,000 C.M., and the size required depends upon the kva. capacity of the welding transformer and length required.

The most common length for cables is between 6 and 8 ft. Should the cables be too short, they are sometimes twisted and bent at too sharp an angle and cables that are too long are disadvantageous because they have a tendency to drag and catch on the projecting parts of the fixtures and the work to be welded, and also require considerably more energy due to their greater reactance.

The welding cable proper is generally made of fine stranded bare or tinned copper wire for flexibility and tinned so that the tin coating acts as a lubricant to the wires in the cable, thus reducing frictional breakage.

While in the above paragraphs rubber covering was mentioned for cables, canvas-covered rubber hose, wire reinforced canvas rubber hose and plain canvas covering are also available and used to a considerable extent.

To obtain maximum life in usage from a welding cable, it should be

properly water cooled. This presents no disadvantage as the welding gun itself is water cooled and quite often the cable itself is used as a medium of conducting the return water from the welding gun back to the outlet. Dry or air-cooled cables, however, have a definite place and are used on certain classes of work. Construction of the cable is essentially the same with the exception of the covering which is generally cotton or canvas covering. When rubber covering is used on dry cables, holes are generally punched in this covering to permit radiation of the heat.

Select as short a cable as consistent with ease in handling in operation, and select as large a cable as possible consistent with good performance of the gun and in keeping with the actual size of the welding transformer and with the thickness and class of material to be welded, for the cables on a portable welder are most subject to abuse and are the most expensive item of maintenance.

GUN WELDING TRANSFORMERS

Gun welding transformers generally have two or more turn secondaries and with necessary links to provide for either a parallel or a series connection of the secondaries, thus effecting additional voltage control. Special transformers are made with multi-secondary turns with provision so that the welding cables can be connected to the various secondary turns to effect the necessary voltage regulations.

This type of portable welding transformer is generally designed and wound to afford high secondary voltages, the average transformer generally delivering from 5 to 20 secondary volts, and built to have a central means of mounting so that it may be suspended by means of the various types of hangers. All suspended transformers should have provisions to provide for safety cable or chain.

Water Cooling

It is essential that portable welding equipment such as transformers, cables, welding guns and electrodes be properly and sufficiently cooled. In cases of very light welding jobs, the series cooling connection can be made from water inlet to the transformer, from the transformer secondaries to the welding gun and thenceforth to the electrodes, and back through a jumper hose to the welding cable and from there to the outlet.

It is advisable, however, on production jobs to individually cool the welding guns, the welding cable and the welding transformer. The accepted practice is to run inlet water to a manifold and from this manifold to individual units with the water return effected in the same manner.

The important thing in water cooling is to have a sufficient supply of clean water, and this water should be vented or returned to the open drain. Any back pressure in the return water line will be a source of trouble and may result in improper cooling.

It is economical in large installations to install a system of piping where all water is returned to a central tank where it is cooled and pumped into the inlet lines by means of a motor-driven pump. For some installations,

this tank is located on the roof and the return water is pumped to the tank and the inlet system is gravity fed. Cooling can be effected by a water-jacketed tank or by an immersed cooling tube.

Quite often necessary water for cooling is pumped either from the well or from a nearby stream. When local conditions warrant, it is advisable to treat this water either with a softener or with a chemical, to prevent hard deposits of mineral which would in turn clog the cooling tubes or to prevent the formation of organic sludge which would also affect cooling efficiency.

High-Pressure Hose

For hydraulically operated portable welding equipment the best grade of flexible high-pressure hose to conduct the high-pressure fluid from the source of supply to the welding tool proper is necessary.

The ultimate bursting strength of the hose is not the only factor that has to be taken into consideration. The use of pulsation welding and automatic repeat welding at high speeds alternates the application and the release of high pressure and has a tendency to destroy inferior hose.

Fittings for this high-pressure hose are of various types and styles, two of the widely used classes being that with a barbed insert with a special wire clamp and that with a special crimped and spun fitting.

Controls

The control of portable welding equipment is generally similar to that of a stationary welding machine, although, however, there are some exceptions. While the simplest of these affords mainly the control of weld time and the control of either the air valve or the solenoid valve on the hydraulic booster, it is advisable to incorporate the squeeze, dwell and cool time to obtain better results, due to the lower ranges of welding pressure application used.

Automatic repeat timers used with portable welding equipment enable the operator to move the guns without operating the trigger for each spot.

Air-operated guns with a remote solenoid valve control or that are directly connected to air-operated contactors (combination contactors and timers) are used extensively and their performance is satisfactory on the majority of the lighter gages of work.

For the welding of heavier gages of metal, hydraulic gun operation with interrupted or pulsation welding control usually is specified.

For the welding of extra heavy metal a special electronic timer, coupled with a welding contactor with two auxiliary mechanical contactors controls the desired sequence of operations. These are single-pole contactors and their purpose is to select a desired welding heat, which is controlled by the timer. Contactor No. 1, for example, is connected to the No. 4 heat of the transformer and magnetic contactor No. 2 is connected to the No. 7 heat of the transformer.

The hydro-booster that furnishes the necessary hydraulic pressure is of the compound type. Two air cylinders of the booster are in tandem and

have individual pistons and individual solenoid control valves for each cylinder.

The operation of the gun is as follows: The operator depresses the control button on the welding gun, initiating the timer; the solenoid valve of the booster is then energized. This brings the points together on the work with a moderate pressure; at the same time, the No. 1 contactor is also energized, closing the transformer primary switch circuit. There follows automatically a series of interrupted applications of welding current to the work proper; with moderate pressure and heat, the work itself is quickly heated to a plastic stage. At this junction, the electronic timer automatically energizes the solenoid of the second cylinder of the booster, thus increasing the pressure on the point, and opens the circuit on the No. 1 contactor and closes the circuit on the No. 2 contactor, thus bringing into effect a higher current value. After a predetermined number of impulses, the entire circuit is de-energized and the weld is completed. The welding gun, cables, welding transformer and pressure mechanisms used must be of heavy capacity, and the operating unit of rugged design.

To summarize: A moderate pressure affords the proper contact resistance between the tip and the work and, combined with a moderate value of current, heats the work quickly to the plastic stage, at which time the higher welding pressure is then applied which, combined with more current and more interruptions, effectively completes the weld.

Hydro-Booster

The hydraulic or hydro-booster is generally used to supply the necessary high-pressure oil for the actuating of the portable hydraulic welding gun. It is essentially an air-actuated hydraulic ram. The admission of air is controlled by a solenoid-operated air valve which, in turn, is controlled by the welding timer proper.

The booster proper consists of two cylinders, the large one at the top being an air cylinder and the small one at the bottom being the hydraulic cylinder. The admission of air into the booster forces the piston down, the end of the piston in the hydraulic cylinder forces the fluid through the high-pressure hose to the welding gun. The air pressure and differential in size between the hydraulic piston and the air piston naturally determine the hydraulic pressure developed.

Different pressures on the welding point proper can be obtained by the following means: A difference in ratio between the sizes on the air and hydraulic cylinders, a difference in pressure of the air admitted to the booster or a difference in the size of the actuating cylinder on the welding gun itself.

FIXTURES FOR USE WITH PORTABLE GUN WELDING EQUIPMENT

There is an unlimited number of styles and types of fixtures that can be designed and built for use with portable welding guns. We will enumerate and describe briefly the following general classes of fixtures.

The important factor in design and construction in this type of fixture is to take into consideration the amount of production, the amount of floor space required or allowed, the particular class of welding tool involved and the possibility of incorporating two or more welding operations while the parts are held in position so that identical assemblies may be obtained.

Fixtures can be built individually and mounted on the table or revolving pedestals. In some cases the base of the fixture may remain fixed and different fixtures mounted to accommodate different sizes and styles of jobs according to the production requirements.

There are no fixed rules governing the design of a fixture, but certain precautions must be followed. Position room must be allowed for the entrance and removal of the welding gun. Clamps should be positioned so as to cause the least interference and also hold the work properly at prede-

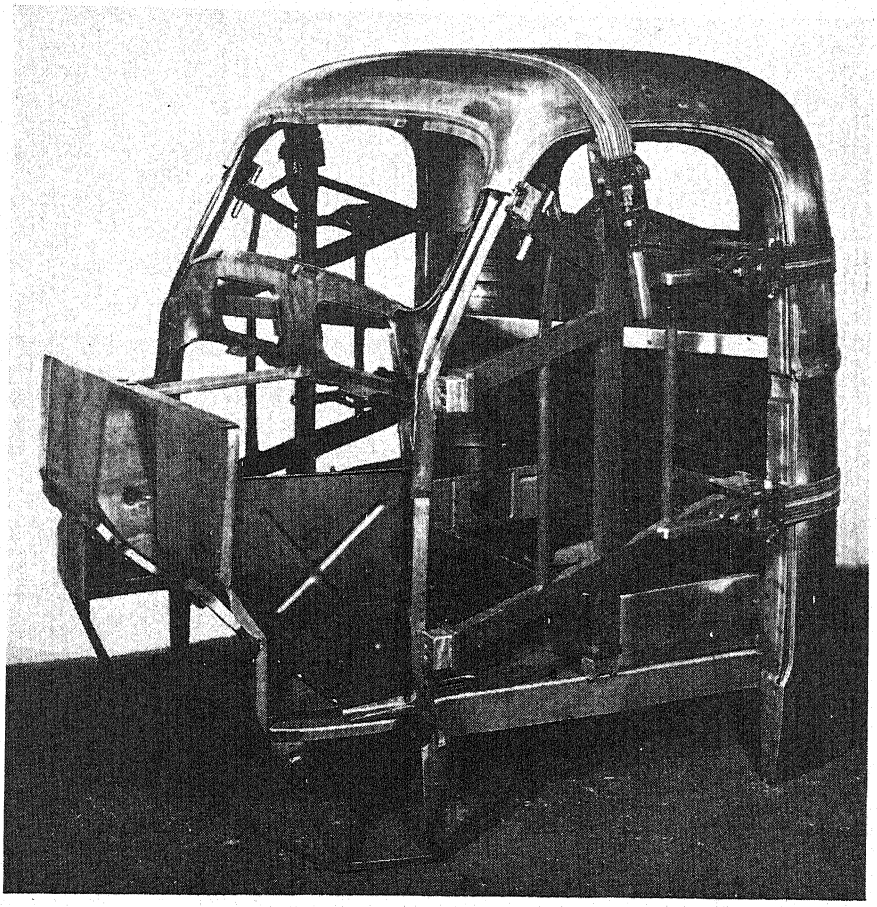


Fig. 20—Combination Locating and Clamping Fixture for Various Sub-assemblies

termined points so the work may be firmly held in the jig while welding. It is wise to bear in mind the fact that too much iron introduced into the throat of the welding gun will considerably lower the efficiency of the tool. This can be avoided by the use of non-ferrous or non-magnetic material. While past experience is an important factor in the building of fixtures and jigs, the same welding principles that govern the entire field of resistance-welding equipment are also applicable to portable gun fixtures.

Types of Fixtures

The simplest type of fixture is a combination locating and clamping fixture for individual loose parts or panels. This fixture is located either by the contour of the parts to be welded or by means of lugs, dowels or locating holes which are introduced in the panel for that specific purpose. The clamping means can be effected either by swivel clamps, quick-acting toggle clamps, cam clamps or other mechanical means. Figure 20 shows a combination clamping and locating fixture in which various subassemblies and the above rear panel are held in correct relationship to one another and the proper shape and alignment of the door opening is maintained by a door plug, and provision is made for additional adjustable cam-operated clamping straps that hold the outer panel in position for gun welding.

On certain types of production jobs, it is advisable to mechanically move the work while the operator remains in a stationary position and performs the welding. This is illustrated in Fig. 21, in which two halves of the gasoline tank are being spot welded into correct alignment and position preparatory to seam welding. This fixture is elaborated by means of a variable speed control for the revolving mechanism and an air-operated clamp to hold the work firmly in place. Different size locators are provided to handle the various sizes of tanks.

Where the loading of various parts into a minor assembly presents a production problem particularly in regard to the amount of time consumed, it is advisable to consider dual fixtures. They permit the welding operator to perform the welding operation while the helper loads or unloads the other fixture.

When confronted with the problem of holding a multiple number of loose stampings and minor subassemblies in order to obtain one complete welded major assembly, not only must the parts be located correctly in relationship to each other, but the locating and clamping means must permit progressive loading and welding of the parts in the fixture.

The fixture must be rugged enough to maintain alignment and, at the same time, to provide sufficient clearance for the positioning of the welding guns and also for the operator to work in a normal position.

Smooth Surface on Work

In the welding fixtures described previously, it was not necessary to consider the problem of the reduction or elimination of the marks or indentations of the spot weld. The majority of these parts were either covered by other panels or assemblies or were in such places that they did

not show. Figure 22 shows a combination welding fixture in which some parts to be welded must show a smooth finish. In this fixture, two halves of the windshield opening must be held in the correct relationship to each other and must also remain flat in order to prevent glass breakage of the windshield proper.

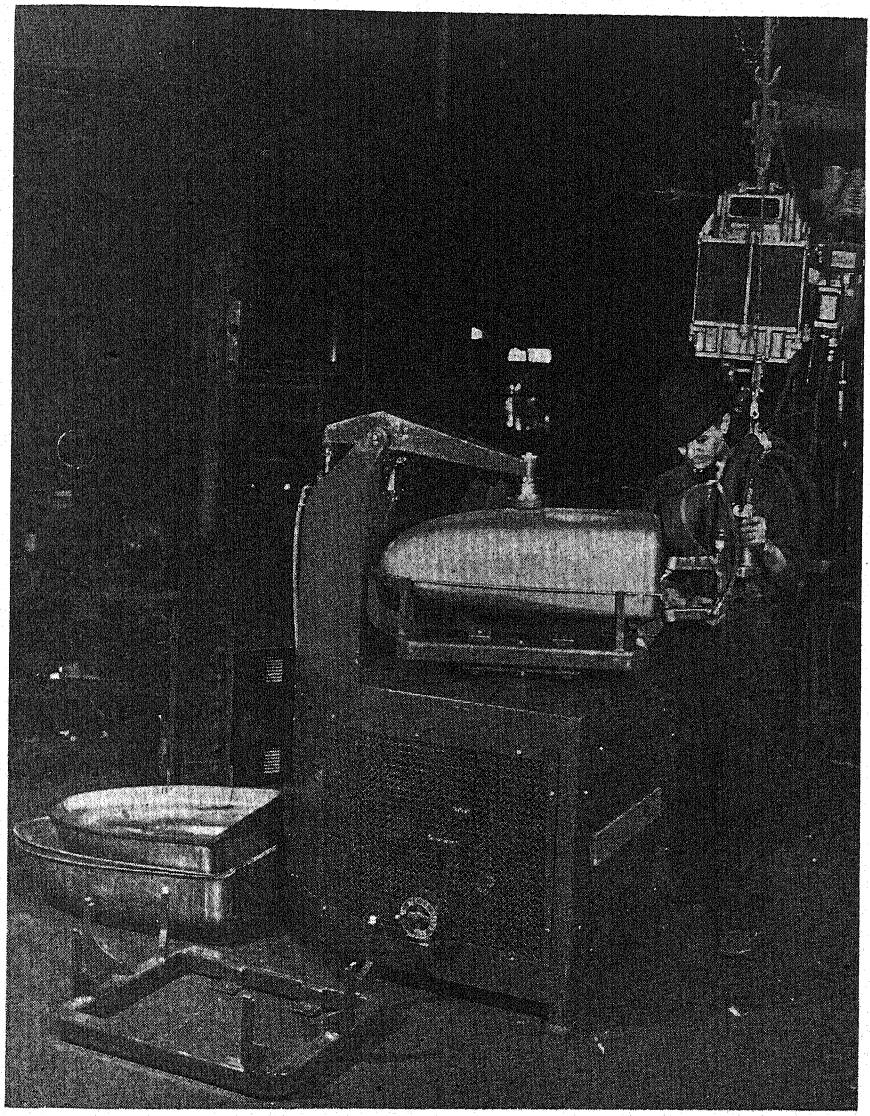


Fig. 21—Mechanically Movable Combination Locating and Clamping Fixture to Move Work While Operator Remains in Stationary Position

These results are obtained by positioning the work on the lower electrode, which is previously heat treated to obtain the necessary hardness, and a conventional type of pinch welder gun is used to perform the welding operation. The welding current passes from the lower tip of the welding gun through the copper electrode to the work; the upper point engages the work itself. The function of the lower electrode of the fixture is to serve as a means of conducting the current and also preventing indentation when welding. This, however, applies to only one face of the work as the in-

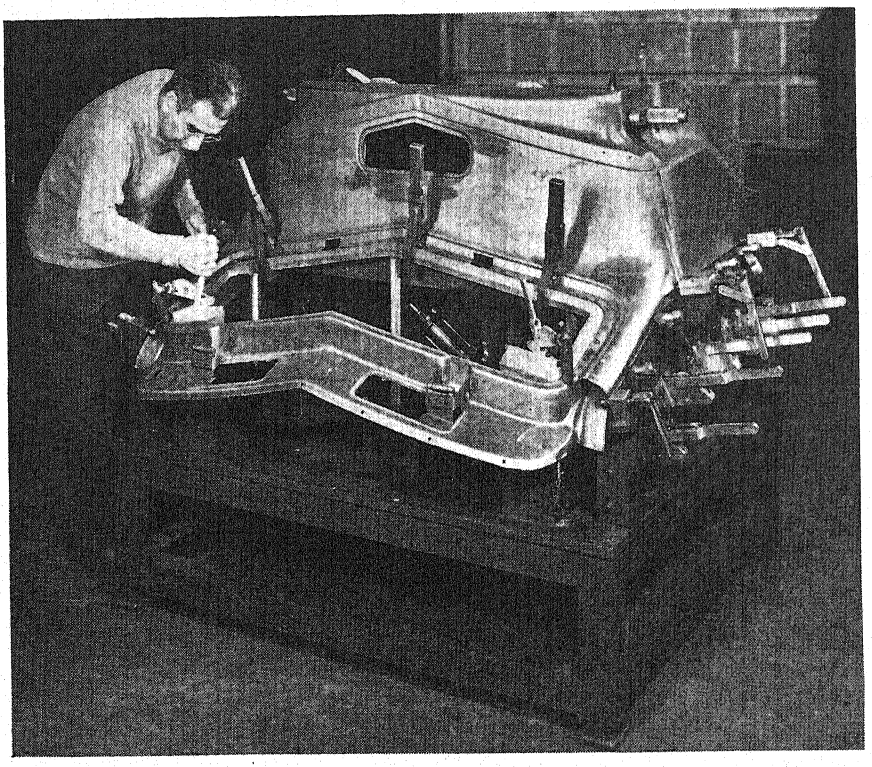


Fig. 22—Combination Welding Fixture in Which Some Parts Must Show a Smooth Finish

dentations will appear on the exposed outer surface of the work where they ultimately will be covered.

Clamping and Sizing Fixture

It is necessary on certain classes of work, particularly on light, curved or formed sections to clamp and securely hold the panels in proper shape while welding to avoid distorted shapes in the finished job. These particular classes of stampings, while uniform in size, are not uniform in shape, and the necessary provisions must be made to overcome this condition.

Figure 23 shows an example of this particular problem. The panels are positioned on locating pads which have been previously fitted to either a master model or to templates. The various pressure pads and locators, which are pivoted, are then swung into position and clamped securely on the work, forcing the panels down into proper shape on the locators proper.

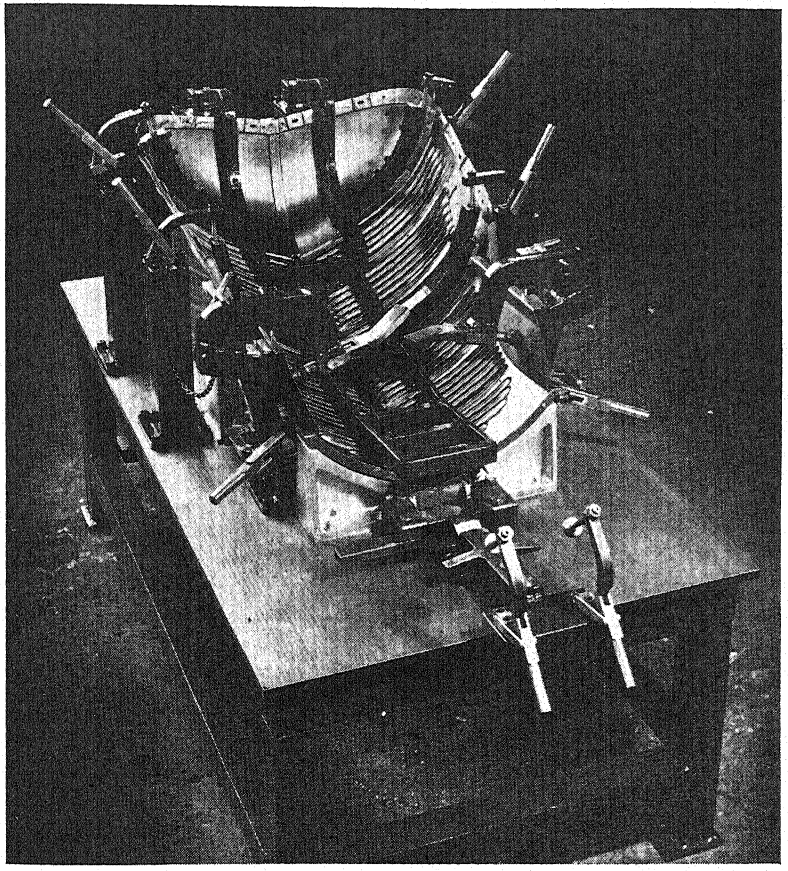


Fig. 23—Clamping and Sizing Fixture

Expansion Gun Fixtures

Expansion gun fixtures, where both the upper and lower conductors are energized and the current is carried to the work, will permit the welding through the means of a short-circuiting type of portable expansion welding gun. The work is located on the lower electrode by means of pins and by the shape of the electrode itself and securely clamped in place by means of quick-acting clamps. The operator then moves the gun manually

from position to position. The hydraulic booster is mounted on a swivel to enable the operator to carry the gun entirely around the fixture; this speeds up the operation and affords ease to the operator.

Dual and Multiple Fixtures

Quite often the loading and clamping time on a job materially exceeds the actual welding time. To keep the welding equipment in constant

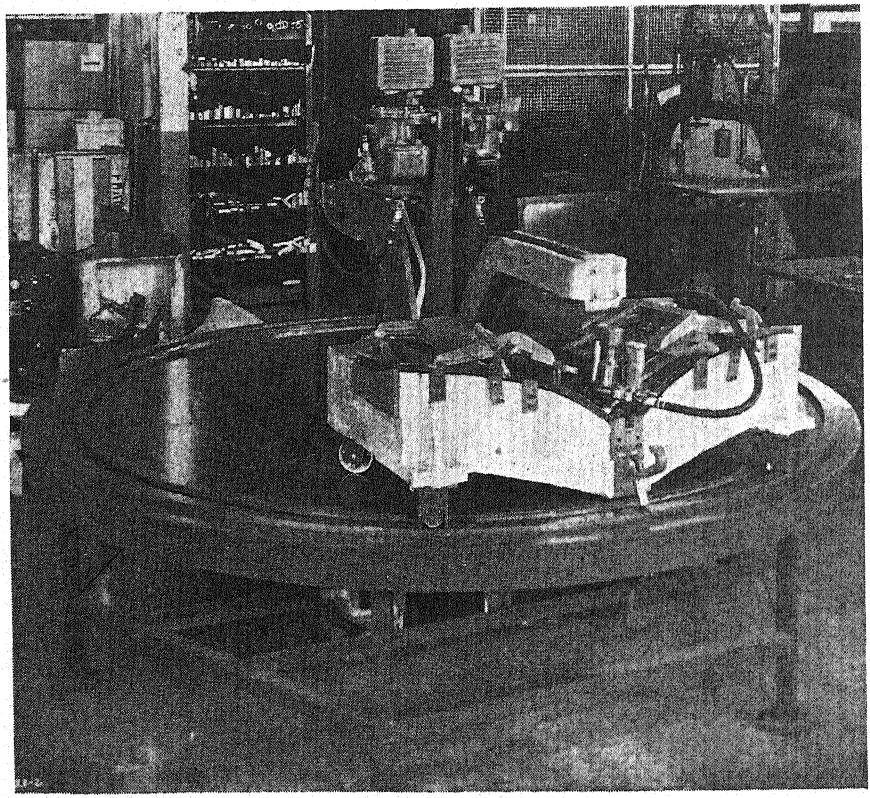


Fig. 24—One Loading and Clamping Fixture of a Multiple Set-Up, Used When Loading and Clamping Time Exceeds Welding Time—to Keep Welder in Continuous Operation

operation, it is sometimes advisable to incorporate two or more fixtures. Figure 24 shows an example of this type of fixture. Only one loose fixture is shown in order to prevent confusion.

The individual parts are loaded and clamped securely in the fixture and the entire fixture is then moved into position under the upper conductor. While one operator with an expansion gun welds the work along the center of the job, two other operators, using a portable pinch welding gun, perform

welding operations at each end of the fixture. This is a combination type of fixture and it has various advantages. The amount of floor space is considerably reduced and the welding operators, who generally have a higher wage scale than other operators are actually welding the greatest portion of the time. This permits the use of helpers who perform the loading, clamping and unloading operation.

Fixture Adaptation to More Than One Size of Work

The question as to how far a fixture can be designed and built to afford interchangeability for various sizes of similar jobs is quite often raised. The answer is dependent upon the amount of production, the time allowed for the changeover and for various pertinent factors of the job itself.

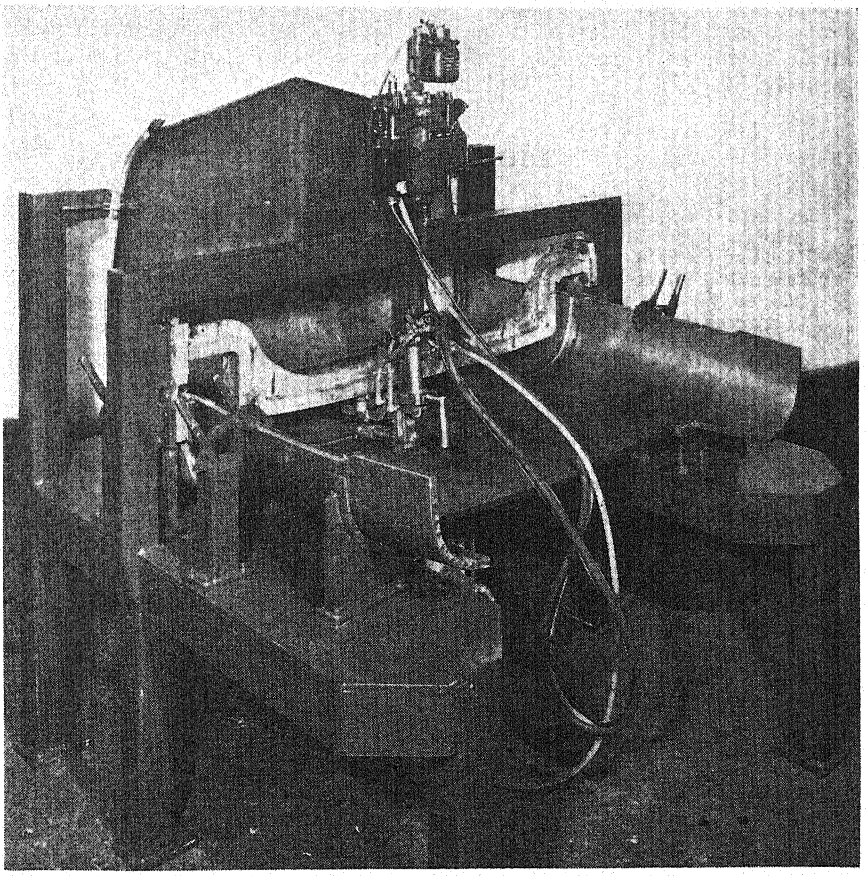


Fig. 25—Scissors Type Short-Circuiting Gun with Conventional Upper and Lower Conductors

Special Gun and Fixture

Some short-circuiting gun fixtures are not of the expansion gun type. In Fig. 25 is pictured a Scissors type, short-circuiting gun with a conventional upper and lower conductor, the same as is in an expansion gun fixture. The reason for this particular design was to accommodate both the welding on the straight surface as well as the welding around the radius.

Conclusion

As stated before, fixtures are unlimited in their design and application. While individual classes and combinations of fixtures have been described and illustrated, they have been of the stationary type. The probable trend of production methods is to style portable welding equipment in a semi-stationary position, locate and clamp the work in fixtures that are mounted on rollers on a turn table, or equipped with casters and moved by means of a chain or a belt past the operator. There is a practice in large production plants of installing different shapes and sizes of guns at different stations and of having each operator perform the welding on one portion of the assembly.

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CHAPTER 11

CONTROLS AND TIMING DEVICES*

Alternating Current Controls, Time Controls, Pressure Controls, Functions of Sequence Controls, Controls for Energy Storage Welders, Measurement Controls and Instruments.

ALTERNATING CURRENT CONTROLS

Heat Control

Welding Transformer Primary Taps.—As discussed under resistance-welding machines, the heat developed in a resistance weld depends upon the magnitude of the welding current, the time of current flow and the resistance of the work pieces where the weld is made. Since the time of current flow is determined by the timing control circuit and the resistance of the weld zone is determined by such factors as electrode pressure, surface condition of the work and the normal resistance characteristics of the work pieces, some means must be provided to vary the welding current when welding different gages of material under varying conditions.

The welding current is equal to the secondary voltage of the welding transformer divided by the impedance of the secondary circuit. The welding current can be changed, therefore, either by varying the secondary voltage or by changing the impedance of the secondary circuit. From a practical viewpoint, it is difficult to change the impedance, as the secondary impedance is determined by the dimensions of the secondary loop circuit and the resistance of the secondary leads, including the work pieces. A more practical method is to vary the secondary voltage.

The open circuit secondary voltage is equal to the voltage impressed on the primary of the welding transformer divided by the ratio of primary turns to secondary turns, or, as it is more commonly referred to, the "turns ratio." Since the secondary usually consists of a single turn, the turns ratio is equal to the number of primary turns in use.

Thus, one method of changing the secondary voltage and also the welding current is to change the number of primary turns on the welding

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* Prepared by a committee consisting of W. F. Hess, Rensselaer Polytechnic Institute, *Chairman;* E. H. Vedder, Westinghouse Electric & Mfg. Co.; J. W. Dawson, Raytheon Manufacturing Co.; F. H. Roby, Square D Company; Dr. F. R. Hensel, P. R. Mallory & Co., Inc.; A. House, R.C.A. Mfg. Company, Inc.; G. W. Garman, General Electric Co.; C. S. Stansbury, Cutler-Hammer Co.; J. A. Weiger, P. R. Mallory & Co., Inc.; W. C. Hutchins, General Electric Co.

transformer. Common practice is to use primary taps, together with a tap changing switch. Increasing the number of turns in use decreases the secondary voltage or the heat, as it is commonly referred to, and decreasing the number of primary turns in use increases the heat.

Autotransformer.—A second method of changing the heat, as mentioned previously, is to change the voltage applied to the primary of the welding transformer. There are two methods in common use for accomplishing this result. One method is to use a tapped autotransformer together with an untapped welding transformer. General practice is to furnish the autotransformer with taps on the output or secondary side, such that the output voltage, which is also the voltage applied to the primary of the welding transformer, can be adjusted from approximately one-half normal voltage to normal voltage. It is relatively easy, however, with this method to increase the range of adjustment by using either lower voltage taps on the autotransformer or to use series-parallel connections on the primary of the welding transformer. If two primary windings are used, they can be connected in parallel for maximum secondary voltage, maximum heat, or they can be connected in series for one-half normal secondary voltage or minimum heat.

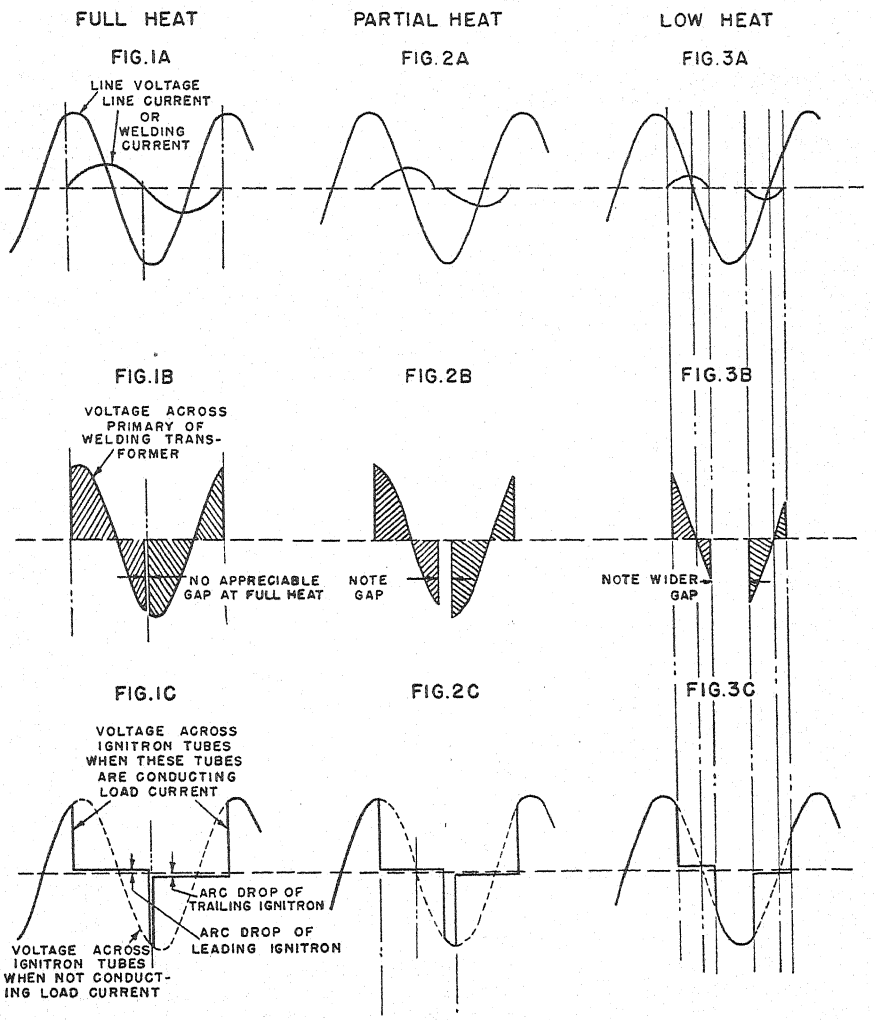
Phase-Shift with Electronic Control.—A second method of varying the voltage as applied to the primary of the welding transformer is accomplished by means of gaseous electronic tubes, such as thyratrons or ignitrons. These tubes when connected inversely in parallel, back to back, are the equivalent of a single-pole switch. When used in this manner, they are the equivalent of a non-synchronous or a synchronous magnetic contactor, depending upon what type of control is used to initiate conduction of these tubes. When allowed to pass current, voltage is applied to the primary of the welding transformer and, when shut off, current flow is stopped. In addition to this simple control feature, they also can be used in such a manner that the effective value of voltage as applied to the welding transformer can be varied through an appreciable range.

The control of the welding current or heat is accomplished by delaying the start of current flow each half cycle. With conventional contactor control using either magnetic or electronic type, the welding current zero is after the voltage zero by the power factor angle. If the tubes are allowed to start passing current at the current zero, current will flow for full half cycles. If the start is delayed until after this point in the current wave, the current becomes discontinuous and is no longer sinusoidal. In effect, the voltage as impressed on the primary of the welding transformer has been reduced, thereby also reducing the welding current.

Referring to Fig. 1-A, the primary voltage of the welding transformer and the primary or secondary current is shown for the full-heat condition, which would also correspond to the voltage and current conditions when either an autotransformer or a tapped welding transformer is used. Figure 1-B shows the voltage appearing across the primary of the welding transformer with a very narrow gap at the current zero, when the current changes from one tube to another. Similarly, Fig. 1-C shows the voltage which appears across the tubes.

Figure 2-A shows the welding transformer voltage and the welding current at reduced heat. It will be noted that current is now discontinuous

as there is a time when there is no welding current. Figure 2-B shows that under these conditions the voltage applied to the primary of the welding transformer is zero. Figure 2-C shows that during this particular interval when current does not flow, or when voltage is not applied to the welding transformer, the line voltage appears across the tubes. It should be noted also that the sum of the voltage appearing across the welding transformer and that appearing across the tubes is equal to the power supply voltage and is sinusoidal.



Figs. 1, 2, 3—Phase Shift Heat Control

Figures 3-A, 3-B and 3-C are similar to Figs. 2, except that the heat has been reduced still further.

The range of current control with this method depends upon the voltage of the power supply and the type of tubes in use. If thyratrons are used complete control can be obtained from the normal or 100% current to zero for all standard power supply voltages.

Ignitrons, on the other hand, require a certain minimum voltage and current to start the ionization process. For this reason, complete control from 100% to zero is not feasible. General practice is to limit the minimum value to 40% rms. current for 220-volt applications, and 20% rms. current for 440-volt or higher voltage applications.

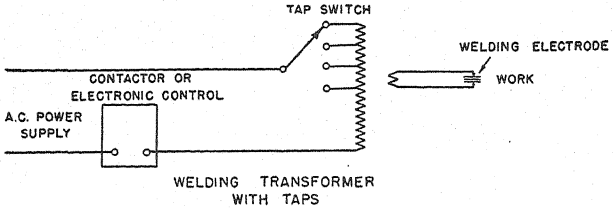


Fig. 4-A

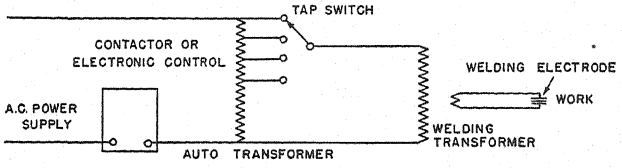


Fig. 4-B

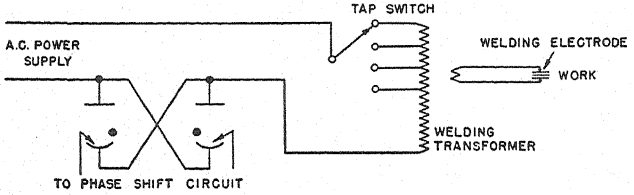


Fig. 4-C

Fig. 4—Illustrating Different Methods of Varying Welding Current or Heat

Reviewing briefly, the welding current or heat can be varied by means of taps on the welding transformer (Fig. 4-A), by means of a tapped autotransformer (Fig. 4-B), by means of gaseous electronic tubes with phase-control (Fig. 4-C) or any combination of these three methods. Heat control by the phase-shift method is of particular value when used either

alone or with any of the tap changing methods, as the current can be changed in very small steps or, as discussed later in the chapter, can be changed quickly and easily from one value to another for special applications.

Switching Devices

In the resistance-welding process power must be applied to the machine for a short but accurate interval of time. The control equipment used consists of a supply line interrupter and means for timing its operation. Interrupters may be of the manual, magnetic, air- or motor-operated or electronic type. The control means used with each is discussed in paragraphs devoted to timing devices.

Manually Operated Contactors.—Current-carrying parts are sometimes manually operated on small foot-operated welding machines. The resulting device called a "pass-through switch," is mounted in a position where a cam on the operating mechanism closes and then opens the switch during a single downward stroke of the foot pedal. Timing is dependent upon the speed with which the pedal is moved. Contactor rating is similar to that outlined for magnetic devices except that maximum values are limited somewhat by slow operating characteristics.

Magnetic Contactors.—Construction: A magnetic contactor is an electromagnetically operated means for repeatedly establishing and interrupting the circuit supplying power to a resistance-welding transformer. It consists of an electromagnet of either one or two poles. When energized, the magnet supplies the closing force and spring pressure opens the contactor after the magnet is de-energized.

The speed and accuracy required for resistance-welder service make careful design necessary:

1. Timing periods as short as $^1/_{20}$ of a second make high-speed operation imperative. Once closed, the contactor must be capable of opening consistently within a very short time interval.
2. Production rates as high as 300 welds per minute demand long mechanical life, if excessive maintenance is to be avoided.
3. The arc drawn at the contact tips must be extinguished quickly to avoid severe overheating and rapid contact deterioration.
4. Current-carrying parts must be properly proportioned, and sufficient spring pressure must be provided to adequately handle the momentary peak loads characteristic of welder service.

In general, standard magnetic contactors intended for industrial service are not satisfactory for resistance-welder applications. Instead, constructions involving near-frictionless bearings, light-weight moving parts, short-contact gaps, strong finger-spring pressure, large cross-section copper parts, special magnet structures and unusual arc-suppressing means have been found necessary.

Nearly all welding transformers are wound single phase. Either single- or two-pole contactors can be used if rated accordingly. Two-pole contactors are rated higher than single-pole units of equivalent size. The two gaps in series provide two points at which energy in the arc can be dissipated, and the voltage maintaining the arc across each gap is reduced.

When two poles are used they may be connected in series on one side of the line or used to break both power lines leading to the welding transformer primary. This latter arrangement may be preferred for safety reasons. On the other hand, a single-pole device is usually considered satisfactory when a two-pole, manual disconnect switch is used ahead of it (see Fig. 5).

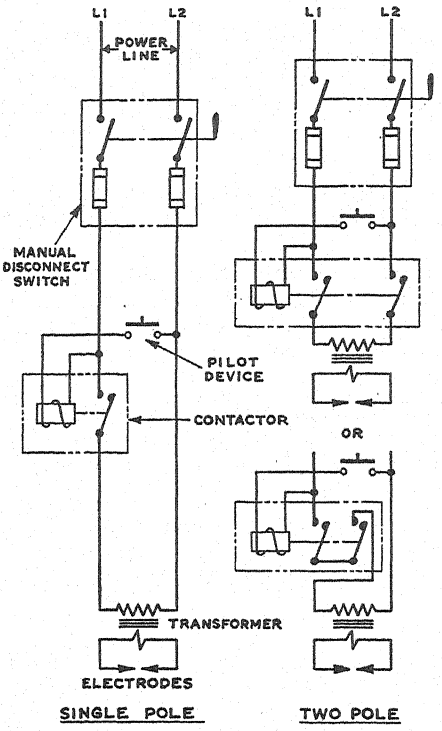


Fig. 5—Contactor Power Circuit Connections

Rating: Welding contactors are identified by the size numbers 0-W, 1-W, 2-W, 3-W, 4-W and 5-W for 50, 100, 150, 300, 600 and 900-ampere nominal ratings, respectively. The nominal rating represents the load which can be carried continuously without exceeding the temperature rise on which the rating was based. It has little meaning except for comparison purposes, since resistance-welding service is usually intermittent in nature. The maximum allowable ratings for a specific contactor design are expressed by a "family" of curves. A typical example is shown in Fig. 6. Each curve within the family represents a different welding time and its contour is determined by plotting the average number of welds made per unit of time against current that the contactor can safely handle under the stated condition. Separate curves are used for single- and double-pole devices, as well as for different voltage and frequency characteristics of the power supply.

Selection of a contactor for a given voltage and frequency is based upon the following factors:

1. Welding transformer primary amperes.
2. Approximate time in cycles for a single weld.
3. The number of welds to be made in a given interval.

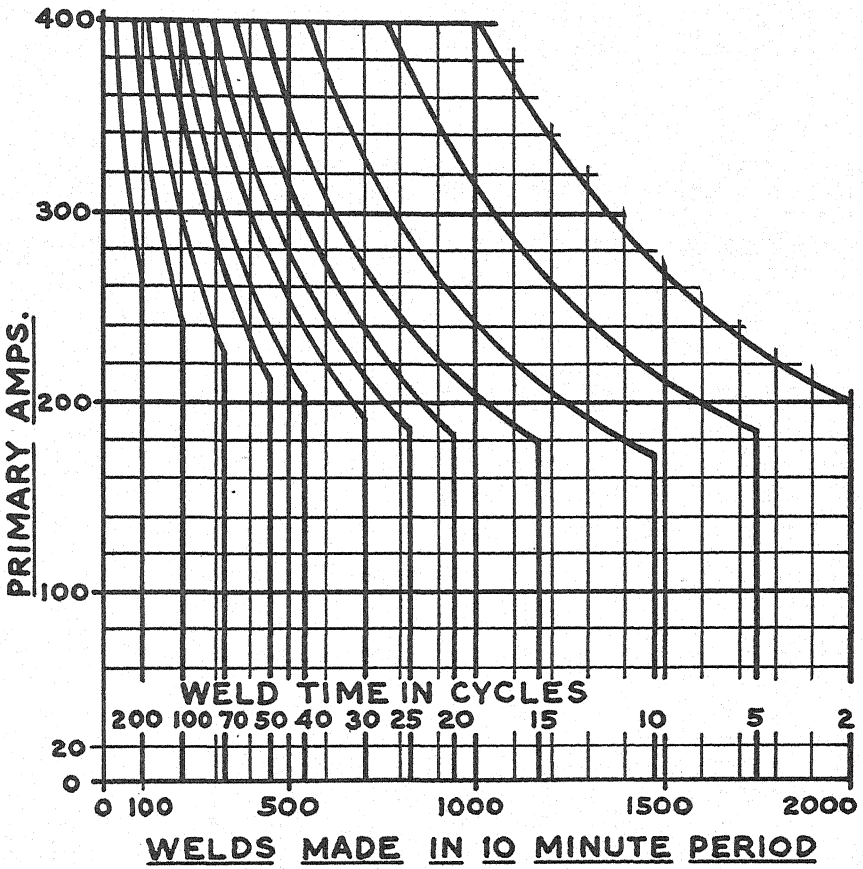


Fig. 6—Rating Curve for Two-Pole, 220-Volt, 60-Cycle Size I Non-Synchronous Magnetic Contactor

The rating of a resistance-welding transformer is usually expressed in kva at a given voltage on a 50% duty cycle basis. A typical welder duty cycle might be as low as 4% and is more likely to be about 10%. Then such transformers can deliver for intermittent periods more than rated current without exceeding the temperature rise upon which the original rating was based.

Example: Neglecting magnetizing current and efficiency of the transformer, a 30-kva., 220-volt transformer would be expected to draw 136 amp. (calculated by dividing 30,000-volt amp. by 220 volts) primary current on a 50% duty cycle basis without overheating. The heat generated in the current

carrying parts is proportional to the product of the current squared, resistance of the material and the time during which current flows ($H = I^2RT$). Then the same transformer used on a 4% duty cycle could theoretically draw as much as the square root of 50 divided by 4 or 3.5 times 136 amp., without exceeding the temperature rise on which the rating was based because $\left(\sqrt{\frac{0.50}{0.04}}\,I\right)^2 \times R \times 0.04T = I^2 \times R \times 0.50T$. In a similar manner a primary current of the square root of 50 divided by 10 or 2.25 times 136 amp. could be drawn on a 10% duty cycle basis without exceeding the temperature rise upon which the rating was based.

Thus the maximum expected contactor load expressed in welding transformer primary amperes can be rather accurately determined by dividing the transformer rating in kva. × 1000 by the indicated voltage of the supply line and then multiplying that quotient by a factor based upon the duty cycle involved. The actual current which flows may be limited by the impedance of the transformer winding but without that factor known, the safe procedure is to expect a current fully as great as the transformer can handle at the duty cycle under consideration. Inasmuch as the character of the welding operation may change from time to time, it is considered wise to select a contactor that is large enough to satisfactorily control the largest current which the transformer might be expected to draw. For this calculation, the factor of four is recommended.

Some few special purpose machines are rated on a maximum demand basis. In that case, the primary current which the contactor would be expected to interrupt is determined by dividing kva. × 1000 by the indicated voltage. No multiplying factor is used.

Welding time is usually estimated on the basis of power available, as well as the nature of both work and equipment. General information on this subject may be found in Chapters 8 and 9, and the welding machine manufacturer's experience may also be consulted. If a special application is involved, sample welds are usually made before a production machine is selected and the welding time is then easily determined by the trial procedure.

The number of welds per unit of time is fixed by production requirements, as well as the nature of both work and equipment. A ten-minute averaging time has been selected to include loading time—the interval during which material is being handled and no welds are made.

With the three factors—maximum transformer primary current, welding time and production rate—known, the correct contactor size is determined by the following procedure:

Example: Assume the need for selecting a two-pole contactor to be used with a welding machine rated 30 kva., 220 volts, 60 cycles. A production estimate indicates that 780 five-cycle welds will be made within a 10-minute operating period. 30 × 1000, divided by 220 volts equals 136 amp. This value, multiplied by a factor 2.5 (compensating for the estimated intermittent duty cycle) equals 340-amp. maximum load that can be drawn from the transformer without exceeding its rating. Select the 5-cycle curve from the family in Fig. 6. Follow the curve to a point on the horizontal reference axis equivalent to 780 welds in a 10-minute period. On the vertical reference axis directly across from that point read a maximum allowable rating of 400 amp. for a Size 1-W device. Thus the Size 1-W is large enough for the 340-amp. load.

Synchronously Interrupting Magnetic Contactors.—Magnetic contactors

which open the power circuit at an instant when the alternating-current wave approaches zero are available. Elimination of the arc usually drawn when the circuit is broken extends the contactor rating and prolongs contact tip life. The selection procedure described in detail for non-synchronous magnetic contactors should be followed, except that the duty cycle can be expressed in number of conductive cycles per unit of time. Separate designations of welding time and welds per minute are no longer necessary because the heating effect of the arc is eliminated and only the temperature rise resulting from copper losses in current-carrying parts remains. Thus the rating chart becomes a single curve instead of a family. See Fig. 7.

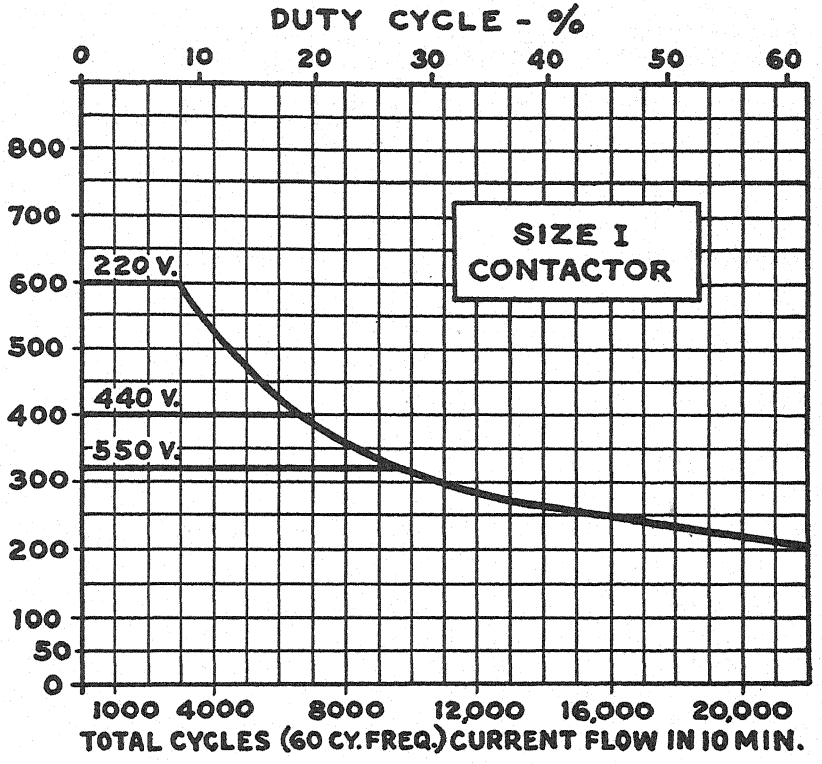


Fig. 7—Rating Curve for Synchronously Interrupting Magnetic Contactor

Maximum ratings are limited at the higher voltages to avoid restriking of the arc across contacts because of ionization of the surrounding medium.

Air-Operated Contactors.—Air-operated contactors may be used with air-operated machines. Mechanical force for contactor movement is supplied by a small air cylinder actuated by means of back pressure from the welding machine operating cylinder. As the contactor piston advances against spring pressure (provided to allow pressure to build up on the electrodes before power is applied) a cam forces the contactor closed and keeps it in

that position until the end of the cam surface is reached. The mechanism is then disengaged and the contactor opens with a quick break action.

Timing of current flow is dependent upon the length of the cam as well as the speed with which it is moved. This latter factor can be controlled by regulating an orifice which admits air to the operating cylinder. Size selection of these contactors is made on a basis the same as that outlined for magnetic contactors.

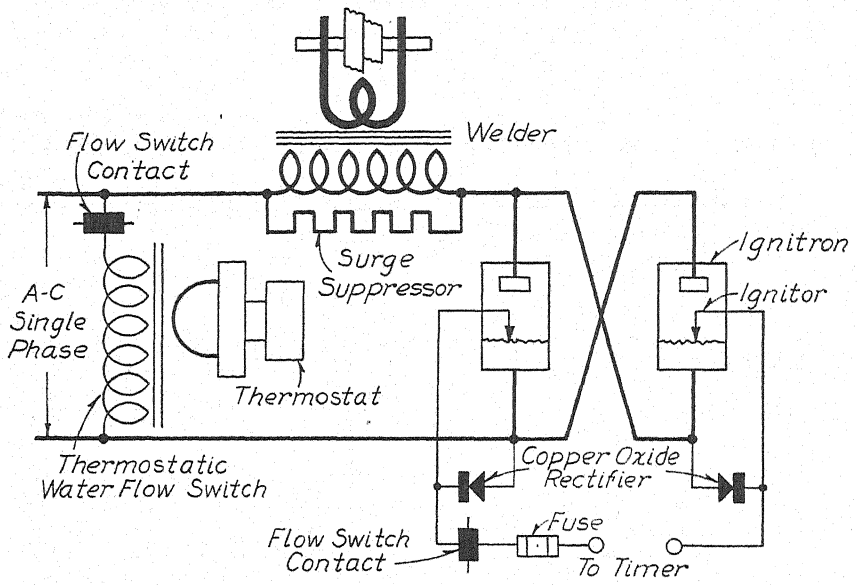


Fig. 8—Schematic Diagram of Tube Contactor Power and Control Circuits

Motor-Operated Contactors.—A synchronous motor may be used to operate a contactor. When the pilot switch is closed a magnetic clutch is energized, thereby connecting the motor to a cam shaft. The cams on the shaft close and open the contactor. At the end of a complete cycle of operation, a relay is mechanically engaged to de-energize the clutch and stop cam shaft motion. The relay forms a holding circuit to prevent repeat operation. The rating is similar to that described for synchronously interrupting contactors. By proper cam adjustment, arcing at the contacts can be eliminated.

Tube Contactors.—Tube contactors are electronic switching devices which control the current to the primary of the welding transformer. The primary current is carried in its entirety by controlled gaseous discharge tubes called ignitrons. The tube contactor is especially valuable for those applications requiring an extremely high number of welding operations per minute or which have extremely high-welding machine current. Either of these conditions imposes very severe duty on mechanical contactors.

Figure 8 shows a typical diagram of a tube contactor attached to a weld-

ing transformer. The tube contactor consists of two ignitron tubes (see Fig. 9) connected in inverse parallel arrangement so that one of the tubes carries the positive half cycle of welding current and the other carries the negative half cycle of welding current. These two tubes together act as a single-pole electronic switch to control the flow of current in the primary of the welding transformer.

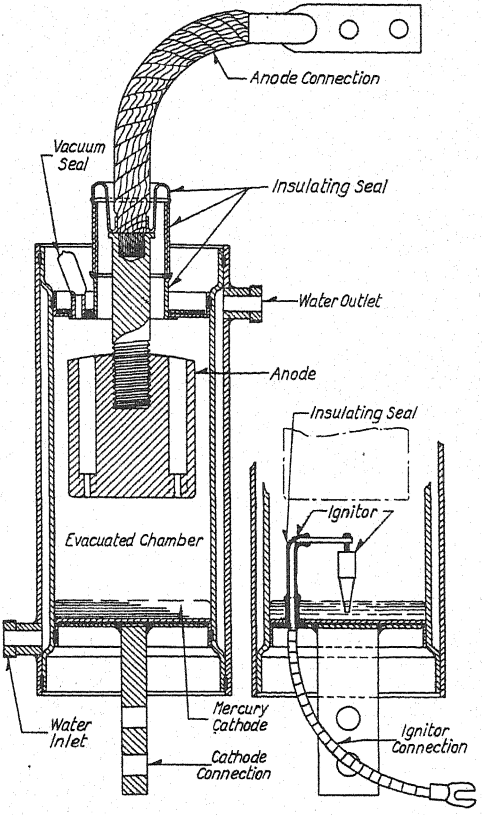


Fig. 9—Cross-Sectional Views of Typical Ignitron Tube Showing General Features of Construction

An ignitron tube is constructed as shown in Fig. 9. The ignitron consists of a steel vacuum tight container with a pool of mercury in the bottom to serve as a cathode, a graphite anode at the top supported by an insulating glass bushing through which the power lead is brought to the anode and an ignitor which is used to start the flow of power in the tube.

Most ignitrons are water cooled and hence have a water jacket made of stainless steel to prevent corrosion. Some ignitrons are cooled by a water-cooled clamp and since the cooling water is not in contact with the ignitron wall, the tube is made of mild steel.

The ignitron is a rectifier since current will flow only from the graphite anode to the mercury pool cathode. Hence, two tubes are required to conduct alternating current, the two tubes being connected in inverse parallel relation as shown in Fig. 8.

The ignitor will cause the ignitron to begin conducting current if a pulse of current is passed through it. The ignitron will not stop conducting current until the current has been reduced to zero which occurs at the end of each half cycle of alternating current. It is then seen that the ignitor must start conduction each individual half cycle during which current flow is desired.

The control circuit of the tube contactor is very simple and is shown in light lines in Fig. 8. The copper oxide rectifiers are connected across each

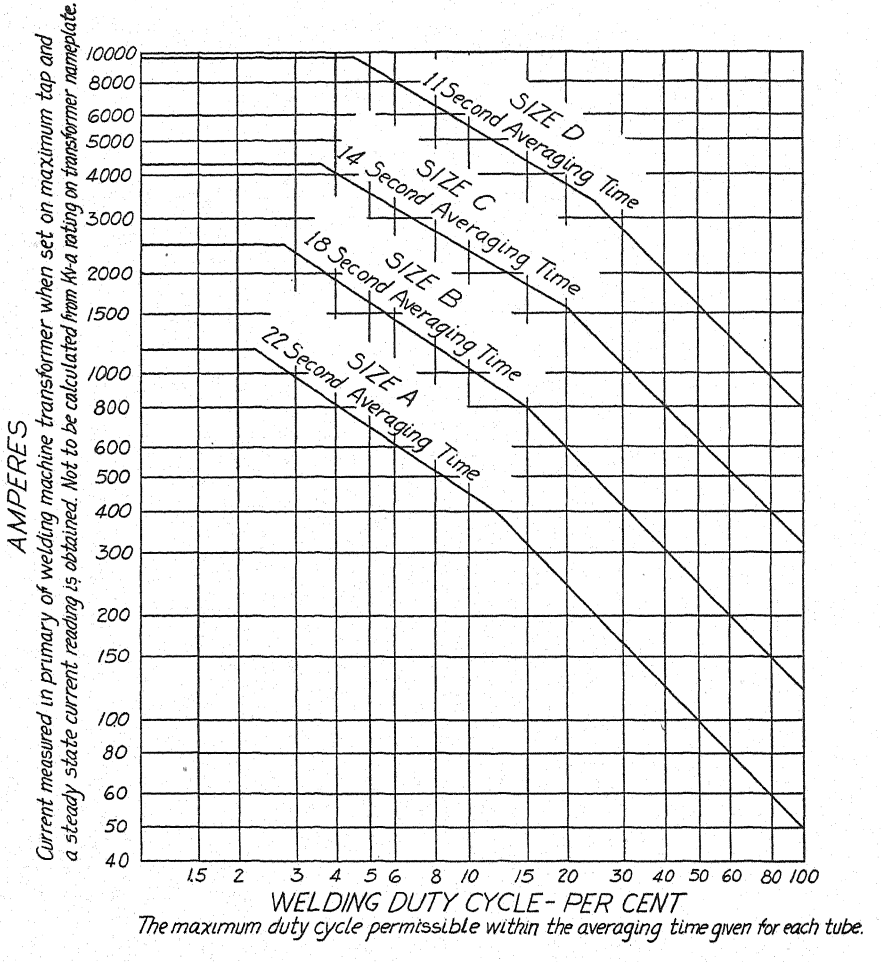


Fig. 10—Typical Ignitron Control Ratings

ignitor to serve as a by-pass for the ignition current required by the opposite ignitron tube. A control circuit fuse is provided for protection of the ignitors and isolating of the remainder of the control circuit from the power circuit. A water flow relay is provided in the tube contactor to insure that the ignitron tubes cannot be operated and become damaged because of the lack of cooling water in the jacket of the power tubes which are water cooled. The timing of the flow of welding current may be done by either a synchronous or a non-synchronous timer attachment connected to the control circuit.

The tube contactor energizes the welding circuit when the control circuit is closed. This control circuit requires no additional voltage, its potential being obtained from the power circuit. Each ignitron is fired for each conducting half cycle by its ignitor which is energized through the control circuit whenever the control circuit is closed by the timer.

A surge suppressor resistor is connected across the primary of the welding transformer, to absorb the magnetic energy which may be left in the welding transformer at the end of the weld and prevent building up high voltage which will cause break-down of the transformer or wiring.

The current-rating of tube contactors depends on duty cycle just as in the case of mechanical contactors. The principal difference in rating between the tube contactor and mechanical contactors is that the averaging time of the tube contactor ranges from 5 seconds up to about 25 seconds depending on the tube while mechanical contactors have about a 10-minute averaging time. Typical rating curves are shown in Fig. 10.

Averaging time as applied to tubes is the maximum time over which duty cycle can be averaged. Thus, duty cycle as used on rating curves is the maximum duty cycle averaged over the "averaging time" for the particular tube. The averaging time is established not only to allow for temperature rise of the parts of the tube but also to take into account the increase of mercury vapor pressure at high ratings when extended over a time interval.

Tube contactors are normally contained in a sheet metal enclosure and provided with inter-connecting bus on which the power tubes are mounted. The box contains fuses, water flow switch, copper oxide rectifiers and an auxiliary control relay if one is desired for operating the timer circuit at low voltage instead of at line voltage.

TIME CONTROLS

Timing Types

As discussed in previous chapters, the heat generated in a resistance weld depends not only upon the magnitude of the welding current, but also upon the length of time that this current flows. The time of current flow is important also, for other reasons. For example, when welding unstabilized stainless steel, it is important that the time be as short as possible; otherwise carbide precipitation will cause the steel to lose its corrosion resistance characteristics. When welding heavier gages of steel intermittent current impulses (pulsation welding) may be of advantage in avoiding ex-

cessive mushrooming of the welding electrodes. Tests have also indicated that cracking and porosity can be reduced in the welding of 24 ST Alclad aluminum with the correct choice of time of current flow and welding pressure. A special timing cycle may be required to obtain a satisfactory resistance weld without excessive hardness or brittleness when the material being welded is one of the medium carbon steels or one of the alloy steels.

It is apparent, therefore, that the time of current flow is of considerable importance, and care must be exercised in the choice of a timing control which will give the most satisfactory results. The choice of the timing control is also affected by the application as to whether spot welding or seam welding is required. For these various applications and for the welding of these various materials, there are four basic types of welding timers when used with a.c. resistance-welding machines.

Single Conducting Interval.—For most spot- or projection-welding applications, particularly for those applications where the thickness of the two pieces to be welded is less than $^1/_8$ in., it is sufficient for the welding current to flow for a definite period of time without interruption. Timers with a single conducting interval are, therefore, known as a single conducting interval type of timer.

The function of a timer of this type is to control one of the various switching devices or contactors in such a manner that the circuit is closed to the primary of the welding transformer for a definite length of time, with the result that the welding current flows for the same interval of time. The time of current flow is usually expressed in cycles of the power supply frequency. See Fig. 11. For example, when making a spot weld in two

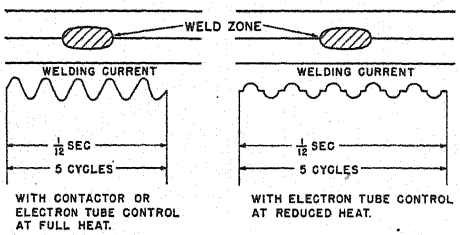


Fig. 11—Spot Welding with Single Conducting Interval Timer

pieces of mild steel, 0.040 in. thick, the time of current flow may be 5 cycles or $^1/_{12}$ second (60-cycle power supply). If electronic tubes, such as the ignitron or thyratron, are used with phase control, the timer functions in the same manner even though the current flow may be interrupted part of each half cycle. (See earlier portion of this chapter on phase control.)

Seam Welding.—The second type of timer is the seam-welding timer. In seam-welding or roller spot-welding applications, the welding electrodes are in the form of wheels between which the work passes. Generally,

pressure is applied continuously and the welding wheels are driven continuously. For most applications, to obtain the most satisfactory results, the current flow must be interrupted at periodic intervals, such that the equivalent of a spot weld is made during each interval of current flow. By interrupting the current flow at definite intervals, the spot has had an opportunity to cool sufficiently so that the heat in the piece being welded will not build up progressively, and possibly cause a hole to be burned through the work. A seam-welding timer, therefore, differs from a spot-welding timer in that the current is interrupted periodically while the rolls still remain on the work and the timer causes current to flow for a definite number of cycles of "on" or "heat" time and the current flow is interrupted for a definite number of cycles of "off" or "cool" time (see Fig. 12). For example, in making a gas-tight seam in two pieces of 0.040 in. mild steel, the timing may be 2 cycles heat time and 2 cycles cool time. This timing cycle is repeated as long as the initiating switch is closed, which is also the time that full pressure is applied to the welding wheel.

By controlling these two intervals of time, the spots can be made close together, thus forming a gas-tight seam, or the current flow intervals can be spaced far apart so that a succession of spot welds is produced. This

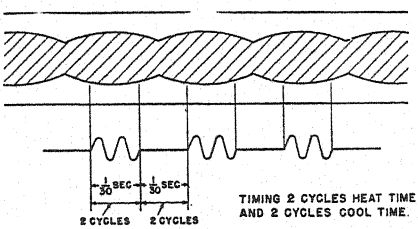


Fig. 12—Seam Welding with Seam-Welding Timer

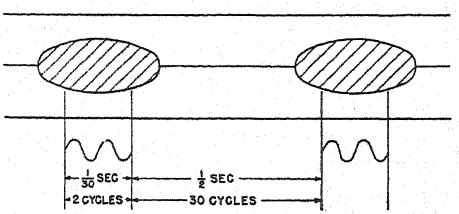


Fig. 13—Roller Spot Welding with Seam-Welding Timer

latter type of welding is frequently called roller spot welding and has the advantage that the production rate is high, as it is not necessary to lift the welding electrode after each spot (see Fig. 13). The seam-welding timer, therefore, has two adjustments, one for the heat time and the other for the cool time.

Pulsation Welding.—The third classification of timers is known as the pulsation-welding timer. These timers are similar to seam-welding timers in that the switching device or contactor is so controlled that the welding current is interrupted at definite intervals. Pulsation welding is used generally for spot or projection welding of heavier gages of metal. If a conventional spot-welding timer of the single-conducting interval type were used, the welding electrodes possibly would mushroom as the water cooling might be insufficient to carry away the heat fast enough without avoiding excessive electrode temperature. In timers of this type, the welding current flows with definite interruption, either for a definite length of time or for a definite number of interruptions (see Fig. 14). For example, if two

pieces of mild steel, 1/2 in. thick, are being welded, the timing cycle may be 20 cycles heat time, 15 cycles cool time, and this cycle repeated 15 times (over-all time, 525 cycles). Pulsation timers have, therefore, three timing adjustments: one, the heat time adjustment in cycles; two, the cool time adjustment in cycles; and three, either an adjustment for the number of interruptions or an adjustment for the over-all time in cycles.

Timers of this type can be used also for seam welding of heavier gages of metal, except that the welding wheels remain stationary during each pulsation interval.

Program Welding.—With the increased use of electronic control for resistance welding, it has been found possible to make satisfactory resist-

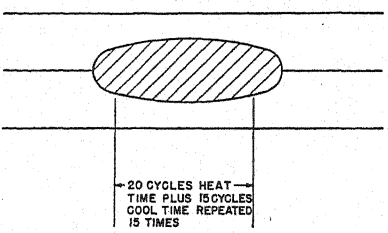


Fig. 14—Pulsation Welding with Pulsation-Welding Timer

ance welds with special timers, which cannot be classified among the three types of timers just discussed. These timers frequently not only cause the current to flow with a variable timing pattern, but also take advantage of the fact that the current magnitude may be changed by means of electron tubes with phase control. An example of a variable timing pattern is given in the table below. Instead of each heat and each cool time being of equal length, the time is varied (pulsation type weld of 9 interruptions).

Heat Time Cycles	Cool Time Cycles
12	6
10	7
9	5
7	5
6	3
4	2
2	2
2	2
2	2

This particular timing cycle is obtained by means of the chain type of synchronous electronic seam-welding timer with the addition of so-called flying contacts. Two flying contacts are used, one at the beginning of this timing pattern and a second one at the end of the timing pattern, such that regardless of when the initiating switch is closed, the timing starts at the beginning of the pattern. With the addition of another flying contact or an additional timing device the heat can be changed from one value to an-

other at any particular point, by the use of electronic tubes with phase control.

Another type of program timer is one which has three timing intervals. The first timing interval is called the preheat time, the second timing interval is called the normal weld time and the third timing interval is called the heat-treat or postheat time. Controls of this type, therefore, have three time adjustments and, if electronic tubes are used, may also have a total of three heat adjustments. These various time intervals may be a single conducting interval, or the current may be interrupted into heat and cool time intervals. If the heat and cool intervals are the same, the timer will include these two additional time elements or adjustments.

A modified form of timer of this type is one in which there is an adjustable cool or chill interval between the normal weld and the postheat time. For example, if each time interval is of the single conducting type, the timing pattern may be: 10 cycles preheat time, 15 cycles weld time, 7 cycles chill time and 30 cycles heat-treat time, with an individual phase control (heat) adjustment for each current flow interval.

An additional type of program timer is one in which the current is caused to change gradually from one value to another over a definite length of time. A control of this type may also include more than one time interval and more than one cool interval with or without the pulsation feature.

These program timers are essentially a combination of standard timers which are described in detail in the following pages. In most cases because of the inherent advantages of electronic tubes they are also used to change the value of the welding current quickly and easily from one value to another.

Timing Devices

Timing devices are classified as to two general types—non-synchronous and synchronous. There are several kinds of each type.

Non-Synchronous Timers

A non-synchronous timer is one which starts and stops the flow of welding current at *random* points with respect to the line voltage wave form. Several factors which may affect the accuracy of the equipment are:

1. A small error in the timer mechanism itself, resulting in variation of the interval during which the operating coil of the welding contactor is energized.
2. Variable amount of arc at the contact in series with the contactor operating coil, thus further affecting the period of energization.
3. Changing closing speed of the magnetic contactor controlling the load, caused by variable transients in the operating coil when energized at random.
4. Distorted transformer primary current wave form caused by transients obtained in random closing of the power circuit and resulting in a variable energy input.
5. Variations in opening of the magnetic contactor controlling the load, as the result of changing conditions of the magnet surfaces as well as the collapse of magnet and shading coil field.
6. Prolonged current flow through the arc frequently drawn at the tips of the contactor controlling the load.

The sum of the errors noted above would be equal to at least a plus or minus one-half cycle and more likely a plus or minus one cycle of alternating-current frequency. This is a relatively small percentage of long timing periods characteristic of some types of work, and as such permits the use of non-synchronous control on a large number of applications. However, an error of this magnitude becomes prohibitive when applied to timing periods of a more critical nature which are needed for the welding of small parts, stainless steel and many of the non-ferrous metals. Then the use of synchronous control is essential.

The descriptions which follow will confirm the fact that the timing of a resistance weld can be accomplished using a wide variety of mechanisms. The selection of one will depend upon the user's judgment of simplicity, reliability of mechanical design, accuracy, convenience of adjustment and general economy.

Electromagnetic.—Timing by the electromagnetic or induction principle is based upon the interval required to discharge energy stored in the field of a specially designed magnet. A direct-current charging source, usually a copper oxide rectifier, supplies a charging current for the system, and the energy stored in the field of the magnet coil is discharged through a paralleled resistance when the charging circuit is interrupted. The time required for the magnet to open is inversely proportional to the value of resistance connected in parallel with the coil—infinite resistance providing the shortest timing period possible with the design of mechanism used.

Electrostatic.—The electrostatic principle is based upon the constant time interval required to either charge or discharge a condenser of a given size, assuming a fixed charging current and a specified value of resistance in the charge or discharge path.

The *condenser charge* system utilizes a direct-current charging source feeding a network system consisting of a condenser having a neon tube and operating coil of a sensitive relay connected in parallel with it (see Fig. 15). The charging rate is varied by means of rheostat (R) and the timing period is equivalent to the interval required to charge condenser (C) to a voltage that will "flash" the neon tube. Flashing of the tube completes the circuit to series relay coil ($CR1$). Closing of its contacts energizes relay $CR2$, which functions to disconnect the coil of welding contactor (W) and thereby remove power from the welding transformer.

"Fixed" Versus "Compensated" Timing.—If the power for the rectifier circuit shown in Fig. 15 is supplied from the secondary of a potential transformer, a "fixed" timing interval will result. That interval is based on the value of charging current, size of the condenser used and the flashing voltage of the neon tube. However, if a current transformer is substituted for the potential transformer, the charging current will vary with the flow of current in the power circuit and a "compensated" timing interval will result. The current transformer will vary the condenser charging current in proportion to the line current. Therefore, the timing interval will be lengthened as the line current becomes less. In a like manner, the interval will be shortened if the line current is greater.

There is a considerable difference of opinion within the industry regarding the benefit to be derived from compensated timing. Without attempting to take sides it might be well to point out that for a large majority of

resistance-welding applications the fixed timing interval has been found to be satisfactory. If compensated timing is used, the current transformer involved necessitates a detailed knowledge of the transformer primary current, as well as appropriate readjustment or reconnection of the controller when changes in heat setting are made on the welder. Then, too, results may be adversely affected by a high inrush transient current if the control is operated at relatively short timing periods. Yet, compensated timing does prove to be an advantage where work surfaces are scaly or otherwise dirty. An appreciable interval may be necessary to complete the circuit through the foreign material on the sheet and that interval could result in an appreciable error in timing, unless the timing interval is initiated by the flow of current in the primary of the transformer. The current transformer coupling which is a part of the compensated timing circuit provides this feature.

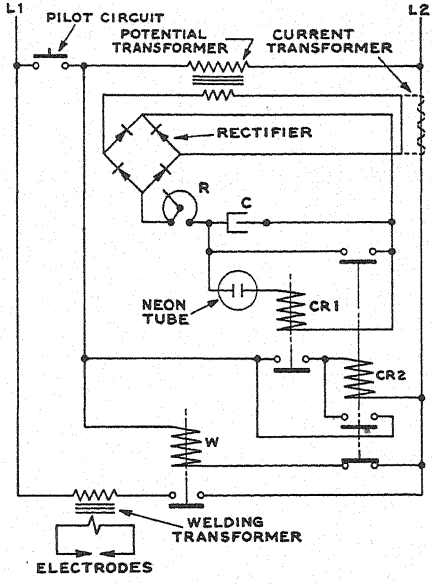


Fig. 15—Electrostatic (Charge Type) Timer

Because heat is proportional to current squared and resistance, efforts have been made to apply a watt-hour principle to compensated timers. Separate windings of a motor-driven mechanism are powered from two different sources—a current transformer connected into the power line and the voltage drop across the electrodes of the welding machine. Since the torque of the motor will then be proportional to the energy in the weld, the timing period would presumably be compensated accordingly. In general, timing devices of this nature have not received a great deal of attention because of the difficulty in applying them and the complicated design.

Pneumatic.—A pneumatic timer is a mechanical device, consisting of an electrical contact actuated by means of a compression-spring loaded rod,

the advance of which is controlled by a delay mechanism involving the transfer of a small volume of air from one chamber to another, through a regulated orifice. The rate of advance of the operating rod (and, therefore, the timing period) is determined by the speed with which air is transferred from one chamber to another through an orifice regulated by positioning a needle valve.

Motor.—Motors having a relatively constant operating speed can be applied for timing purposes. The cam-operated contacts close and open the circuit to the operating coil of the welding contactor. A clutch is sometimes used to engage and disengage the cam shaft, allowing the motor to run continuously. Occasionally the cam shaft is directly connected to the motor which is then started and stopped at the beginning and end of each timing period.

Synchronous Timers

A synchronous timer (1) provides an accurate timing period and (2) both closes and opens the primary circuit of the welding transformer at precisely the same point with respect to power circuit voltage in making each weld. Thus the current wave form is consistent and the energy delivered to the welding transformer is the same for consecutive operations.

The control of the point at which the power circuit is closed is vital to precision results. If the highly inductive circuit characteristic of a welding transformer is connected to the power circuit at a point corresponding to zero current (if current were flowing), then no transient will occur and the current during the first half cycle will be practically the same as the steady state current throughout the making of the welds. On the other hand, when the power circuit is closed at the time the current would be

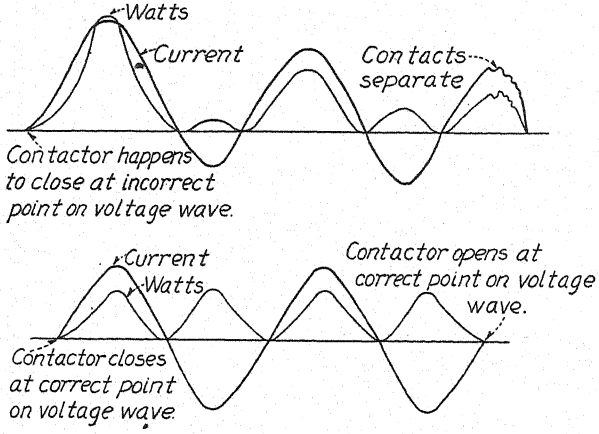


Fig. 16—Curves Showing Difference in Current and Watts Waves When Circuit Is Closed Synchronously and Non-Synchronously

(a) Shows closure of the circuit at the incorrect point a resultant decaying transient. The opening is also non-synchronous. (b) Shows synchronous opening and closing of the circuit at the point of zero current corresponding to minimum transient.

maximum (if current were flowing), a transient primary current results. Its peaks are greater in magnitude than those corresponding to normal or steady state currents. The transients in the secondary winding of the transformer are not so great but they are sufficient to materially affect the energy delivered to the weld.

Figure 16 shows two waves of a.c. welding current, one of which is the type of wave obtained with a synchronous timer for all welds and the other is the type which occurs to a greater or lesser degree in a random manner when using a non-synchronous timer.

The nature of the transient resulting from any particular closing of the primary current depends upon the magnetic condition of the transformer core, the connected load and the point on the voltage wave at which the circuit happens to be completed. Since the magnetic condition of the core depends upon the magnitude and direction of the last preceding current flowing in the transformer winding, it is evident that the point of opening as well as closing of the power circuit must be controlled if uniform results are to be obtained.

For minimum inrush transient currents, the initial half cycle of current must be in the direction opposite to that last flowing and the circuit must be closed at approximately the peak value of the supply voltage wave—the exact point being determined by the power factor of the circuit, since it determines the instant that the current would be zero, if flowing.

Synchronous timers may be needed for fabrication of materials which have a narrow plastic range. Aluminum, brass, copper and others of the non-ferrous materials are in this group. In addition, synchronous timing is necessary to avoid too large a percentage of error where timing periods are less than three cycles in duration. Short time welds requiring as little as one half cycle to make result in extreme localization of the heat and provide for reduction in (1) volume of heat-affected zone, (2) surface oxidization, (3) distortion, (4) electrode wear and (5) power consumption.

Electronic.—Figure 17 illustrates a type of control that has been very successful as a precision device. Ignitron tubes of the type previously described are used as interrupters, instead of magnetic contactors. Control of these tubes is accomplished by means of three hot cathode-type thyratron tubes which provide "triggering" impulses that start and end the timing period. When the control circuit is closed, tubes (2) become conductive at the first peak voltage or impulse derived from the triggering circuit consisting of tube (1) and transformer ($TR1$). Conduction through tube (2) raises the potential of the junction between resistors ($R1$) and ($R2$), thereby making the firing tubes (4 and 5) conductive. These, in turn, cause the power tubes (A and B) to fire, and power is delivered to the welder transformer. After a definite period of time determined by the value of resistor ($R4$), condenser ($C2$) charges enough to fire tube (3). This action reduces the potential of the junction ($R1$, $R2$), stopping conduction through both intermediate and power tubes.

Hot cathode-type thyratron tubes are sometimes used in connection with a transformer having its primary connected in series with the welding transformer to interrupt large currents. When the tubes are not conductive, the secondary of the series transformer is opened and its primary winding acts as a choke, reducing the voltage across the welding trans-

former to about 5% of the supply voltage. If made conductive, the tubes short circuit the secondary winding of the series transformer, thus reducing the primary impedance so that about 95% of line voltage is applied to the welding machine.

The fully electronic circuit eliminates the errors normally associated with non-synchronous control and also provides for the use of "heat control,"

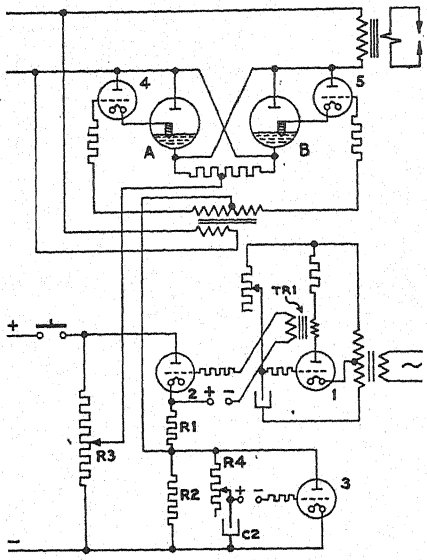


Fig. 17—Fully Electronic Spot Welder Control

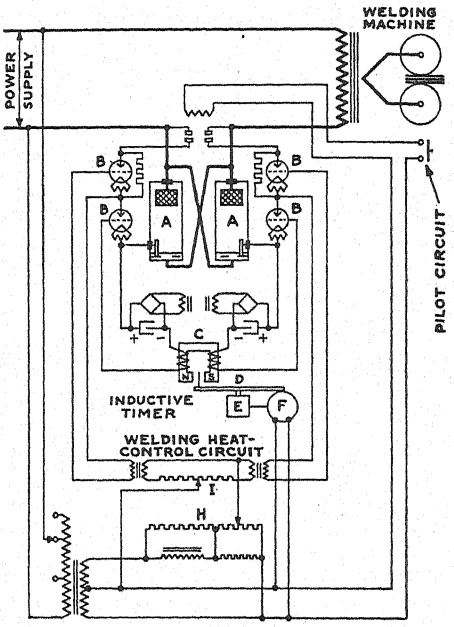


Fig. 18—Electronic Seam Welder Control

more fully described in preceding paragraphs. Ignitron power tubes must be re-ignited each half cycle. By controlling the point of energization, the energy delivered to the weld within a specific period can be varied in an infinite number of steps without resorting to the use of a tap switch in the primary of the welding transformer. This adjustment is of considerable importance when work of a critical nature is under consideration.

Fully electronic control is also used for seam-welder applications. Machine electrodes are in the form of rollers which apply pressure to the work as it is moved between them. To localize the weld it becomes necessary to interrupt the flow of primary current at frequent intervals. From 10 to 16 current interruptions per inch of work are not unusual. Assuming an average feed rate of about 90 in. per minute, between 900 and 1200 interruptions per minute are required. Mechanical interrupters cannot be expected to have long life operating at such speeds.

Seam-welder control consists of two ignitron power tubes and some means for determining the interval during which they are conductive

An electronic timer can be used for this purpose, or a synchronous motor-driven mechanical means may be substituted. The circuit shown in Fig. 18 utilizes a synchronous motor-driven timer consisting of an aluminum alloy timing disc (*D*) containing 120 holes evenly spaced about the rim. When rotated once per second, each hole represents one half cycle. Steel pins, plugged into the holes corresponding to the intervals during which welding current is desired, pass between poles of a small permanent magnet upon which coils are mounted. The voltage generated in these coils by passage of pins causes control tubes (*B*) to fire and pass current through the ignitor circuit of the larger power tubes (*A*). Various timing cycles are established by altering the pin arrangement. A typical seam-weld timing cycle might consist of two cycles "on" and three cycles "off."

An equivalent arrangement consists of a synchronous motor driven adjustable link chain composed of master links with conducting or non-conducting buttons that can be arranged in the order desired by the operator. Each button represents one half cycle of power supply. The point at which the ignitron tubes are energized with respect to the voltage wave can be controlled by adjusting potentiometer (I). This phase shifting means, sometimes called "heat control," determines the active portion of the half cycle during which current is delivered, thereby controlling the power supplied to the weld without need for the usual tap switch on the primary of the transformer.

Mechanical.—An early effort to make available a simplified form of synchronous control resulted in the motor driven contactor. Closing the pilot switch energizes a magnetic clutch, connecting the motor with the cam shaft. Cams on the shaft close and open the main line contacts and then mechanically lift a relay that disengages the clutch. At the same time the relay "holding" circuit is formed. The push button must be opened to release the relay and prepare the circuit for another operation. A maintained contact switch allows repeat operation when desired. Although simple in design, the motor-driven contactor has been found rather difficult to adjust and maintain, because of mechanical wear on gears and moving parts. In addition, the results are not considered sufficiently accurate for some types of work.

The so-called impulse contactor is a more recent development. Energy stored in a condenser is discharged into the operating coil of the magnetic contactor, causing its contacts to close and open at points determined by the inertia of the moving parts, the character of the contact finger spring and the quantity of energy delivered to the operating coil. The equipment involved has a limited operating range and proper adjustment is sometimes difficult because of the several related factors which influence the final setting.

The development of a synchronized opening magnetic contactor made possible the use of a *synchronous motor-driven timing device with two magnetic contactors operated in sequence* to accomplish a precision weld.

PRESSURE CONTROLS

The three major variables in resistance welding are:

1. Welding current.
2. Current duration.
3. Pressure.

The discussion of the pressure variable will be confined primarily to the subject of the spot-welding process.

The pressures encountered in resistance welding may be defined with reference to the effects accomplished and fall into two general classifications.

(*a*) The pressure exerted in driving the moving electrode members in and out of engagement.

(*b*) The pressure actually applied to the material being welded.

In some types of machines both pressure effects are obtained from the same pressure source, while in other types of welders each pressure effect is acquired from an independent source.

The pressure (*b*) is of prime importance and constitutes the pressure variable in resistance welding.

General Functions of Pressure in Resistance Welding

The welding pressure applied through the electrodes to two sheets of metal being welded accomplishes a number of definite purposes:

1. It forces the materials to be welded into intimate contact.
2. It tends to break through films of oxides and absorbed gases that are found on the surface layers of the materials to be welded.
3. It presses the sheets to be welded together and restricts the passage of current to this area.
4. It reduces the formation of porosity and cracks in the welded area.
5. It aids in reducing the losses of low boiling point elements.
6. A substantial pressure maintains a low value of contact resistance between welding tips and sheet to be welded, reducing the tendency to sticking or alloying of the electrodes to materials being welded.
7. It provides a small deformation in the crystals of the materials to be welded and allows recrystallization across the interfaces.

Influence of Pressure on the Quality of Spot Welds

The force applied to work to be welded, the method of application and inertia of the moving parts will greatly influence the quality of a spot weld.

The Effect of Pressure on the Contact Resistance

In the basic formula giving the heat generated in a spot weld

$$H = KI^2RT$$

The factor R is to a considerable extent dependent upon the applied pressure. The electrical resistance R includes the contact resistance between the electrodes and material being welded, the contact resistance between the interfaces of the materials being welded and the specific resistance of the metals being welded.

To illustrate the effect of pressure on the contact resistance the graph,

Fig. 19, is a pressure-resistance curve made on two sheets of 18–8 stainless steel. The curve in Fig. 19 was determined at room temperature without actually performing a weld. The pressure resistance curve will vary with the surface condition of the materials for a given material.

The nature and change of the contact resistance during welding is a complex phenomenon and involves such factors as the physical properties of the surface films, the persistence of the pressure application and the variation of the physical properties of the metals and surface films with elevated temperatures.

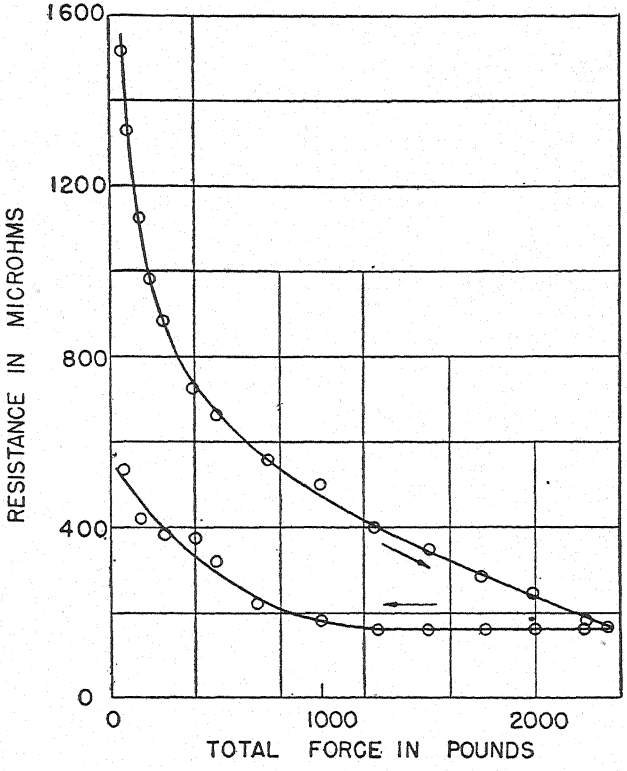


Fig. 19—Pressure-Resistance Curve

As the pressure is increased the contact resistance decreases and in accordance with the heat formula, for a given condition of the materials being welded, this decrease in resistance will require a greater amount of current to develop the same amount of heat in the same time interval.

The decrease in resistance with increased pressure will allow more current to flow but this effect will be small in most conventional welders. It might appear desirable to decrease the pressure and thus increase the resistance, enabling the use of a lower current consumption. However, the use of low pressures is conducive to several undesirable features.

A low pressure may cause sparking and sticking between the electrodes and sheet, resulting in rapid electrode deterioration and unsatisfactory appearance of the spot weld. It may not produce sufficient forging pressure to prevent porosity or cracks in the weld area.

Factors Influencing Variations of Pressure

1. Inertia Factors Connected with Pressure Application Systems.—Certain metals and alloys which include copper alloys and aluminum alloys require precision control in spot welding and are welded using very short weld time periods such as $^1/_2$ to 5 cycles.

In many ordinary spot and seam welders, the great mass and relatively high inertia of the welding head and electrode assembly delay the follow-through movement necessary to produce a good weld. There are also considerable frictional forces to overcome, such as friction resulting from packing, metal to metal surfaces, etc. This failure to secure a follow-through movement may result in flashing between electrodes or blowing out of the weld metal, requiring redressing of electrodes.

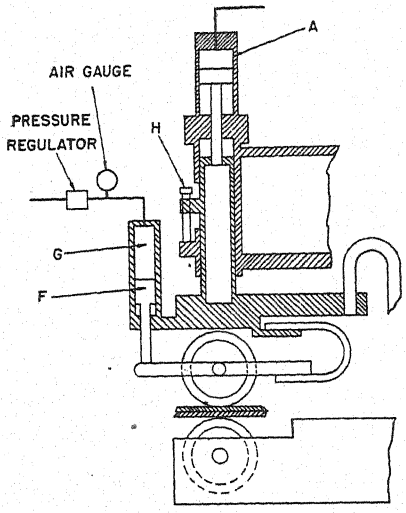


Fig. 20—Low Inertia Seam Welding Head

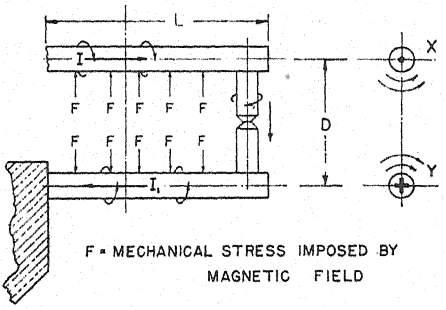


Fig. 21—Magnetic Effects in Secondary Loop

The time required for the restoration of electrode pressure after any sudden reduction in weld section, neglecting friction, is a function of the distance to be traveled, the mass of the moving system and the force available for acceleration.

The fundamental formula expressing the relationship between the acceleration of a mass by an applied force is given below:

$$\text{Acceleration } (a) = \frac{\text{Force } (F)}{\text{Mass } (M)}$$

Force is expressed in pounds, mass is expressed in slugs or weight in

pounds divided by the gravitational constant (32.2), and acceleration is expressed in ft./sec./sec.

For example, assume a movable electrode assembly of a spot welder weighing 80 lb. Neglecting frictional forces, the acceleration of this system with an applied force of 800 lb. will be

$$a = \frac{800}{80/32.2} = 322 \text{ ft./sec./sec.}$$

The distance S which the electrode will travel in a certain time such as $^1/_2$ cycle (0.00832 sec.) is calculated from

$$s = \frac{at^2}{2}$$

$$= \frac{322 \times 0.00832^2}{2} = 0.0111 \text{ ft.}$$

or $$S = 0.133 \text{ in.}$$

The formula indicates that it would be desirable to reduce the mass of the moving members to a minimum, thereby providing more rapid acceleration of the electrode assembly. Many of the modern spot and seam welders are designed with moving members incorporating low inertia moving parts. The most common is the airlock type, which consists of an auxiliary cylinder and piston built into the lower end of the movable electrode assembly.

The diameter of the main piston is slightly larger than that of the airlock piston. When similar air pressures are applied to both pistons the force applied to the main piston is greater than the air lock force. The stroke of the welder is adjusted so that the air lock is collapsed slightly by the force of the main piston when the work is engaged.

The mass of the air lock piston and its electrode assembly is only a small portion of the entire quill assembly.

A seam-welder quill assembly incorporating a low inertia head component is shown in Fig. 20.

This diagram illustrates the arrangement for a general type seam welder with the upper head actuated by an air cylinder. Only enough pressure is applied to this cylinder to bring the entire assembly into welding position. This is accomplished by applying air pressure to cylinder A. Once contact with the work has been established, any further pressure is cushioned by the upward movement of piston F in cylinder G. Set screw H attached to the main spindle permits adjustment of piston A, and relieves the work from all pressures resulting from the dead weight of the head assembly. Actual welding pressure is supplied by cylinder G in which air pressure can be accurately regulated by a pressure regulating valve. The only pressure applied to the work is that which is exerted under close regulation by the small cylinder.

There are many designs of low-inertia electrode holders, some of which are mechanically operated with spring pressure mechanism while others are air pressure devices.

A great many are designed as auxiliary holders which may be conveniently attached to standard welder arms or plates. They greatly increase the flexibility of many types of spot and projection welders by providing a lower pressure or a low-inertia head assembly.

2. Mechanical Forces Created by Magnetic Field.—A factor which must be given consideration is the magnetic stressing of the members of the secondary circuit when current is flowing. This magnetic stress tends to force open the electrodes and therefore the effective pressure is the force applied to the electrodes minus the counter force imposed by the magnetic stressing of the secondary circuit.

Two parallel wires carrying current in opposite directions tend to repel each other, while two parallel wires carrying current in the same direction tend to attract each other.

In a welder secondary loop, as shown in Fig. 21, the magnetic field may be intense and the conductors tend to repel each other.

In Fig. 21 the welding current is flowing in the direction I and I_1. The electrodes are held in engagement by an applied force. The magnetic lines of force set up by the current in each arm projection are in the direction shown by the concentric circles looping the conductors. The sectional view is shown by conductors X and Y.

The magnetic stress in this system is directly proportional to the depth of the throat l and inversely proportional to the separation or distance between the arms D. It is also proportional to the square of the secondary current.

There is also a field set up by the holders in the vertical direction but since this field is parallel to the arm projection, it does not exert a force tending to spread the arms apart.

The magnetic field set up by the current in the arms tends to separate the arms with a force expressed by the formula

$$F = 9I^2 \times 10^{-8} \left(\frac{l}{D}\right) \text{(lb.)}$$

where I is in amperes flowing.

The formula gives the maximum momentary value of the force and since the current is alternating, this mechanical force tending to separate the arms is pulsating.

The effectiveness of this pressure created by the magnetic field in actually subtracting from the total welding pressure is, to a large extent, dependent upon the inertia and frictional forces of the moving members under dynamic conditions and the mechanical design of the arms and movable structure.

3. Surface Irregularities in Material Being Welded.—Another factor leading to inconsistency in effective pressure, particularly when spot welding relatively heavy stock, is that a portion of the total pressure applied may be absorbed in eliminating a buckle in the materials being welded.

The pressure necessary for straightening or forming the work pieces must be deducted from the total applied pressure to obtain the effective welding pressure.

Correlation of Pressure and Currrent Cycles

The current dwell period during welding should be properly synchronized with the pressure cycle. By this statement is meant that full pressure

must be applied to the weld materials before the welding current is permitted to flow and the full pressure should persist after the welding current is cut off, thereby allowing the weld to cool under pressure.

Mechanisms for Application of Pressure

There are many types of pressure applying mechanisms available with resistance-welding machines, practically all of which incorporate devices which permit a wide and quite readily adjustable variation in pressures applied to the materials to be welded.

In resistance-welding machines of modern design the sources of pressure fall into three general groups: (*a*) spring, (*b*) air, (*c*) hydraulic.

In some types of machines a combination of two or more of the methods are employed.

Manually Operated Rocker Arm Type Welder.—Figure 22 shows a simple manually applied pressure system of a rocker arm type welder.

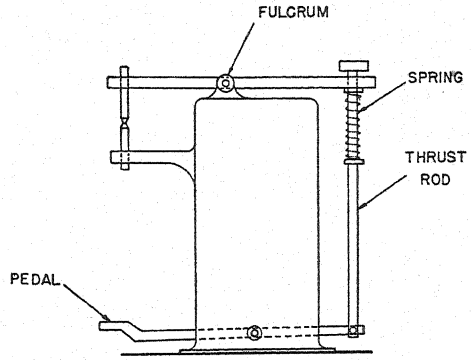


Fig. 22—Manually Operated Rocker Arm Spot Welder

In this type of pressure arrangement the operator applies a force to the pedal of the welder, which forces the electrodes against the materials to be welded. Further force applied to the pedal compresses the spring through a mechanical advantage gained by the lever system.

With this system it is possible for the operator to apply a pressure to the materials being welded many times that which is applied to the pedal. The ratio of these pressures is determined by the mechanical advantage afforded by the lever system. The force applied to the electrodes is the product of the amount of spring compression and the mechanical advantage of the lever system between the spring and the electrode points.

Manually operated machines, such as described above, are limited to relatively low pressure, due to the fatigue of operators when rapid production is encountered. In general, the manually operated machines are built for pressures not exceeding 300-lb. total pressure on the electrodes. The pressure may be varied or may be held constant by means of a stop which limits the compression of the spring to a predetermined amount.

Mechanically Operated Rocker Arm Type Welder.—To reduce operator fatigue and maintain high-production levels, the manually operated machine of this type is equipped with a motor-driven cam or an air-operated cylinder mounted on the thrust rod of the welder serving the same purpose as the foot pedal.

In some types of machines the operator may operate the pedal to bring the electrodes into engagement while a motor-driven cam applies the actual welding pressure. A machine of this type is shown in Fig. 23.

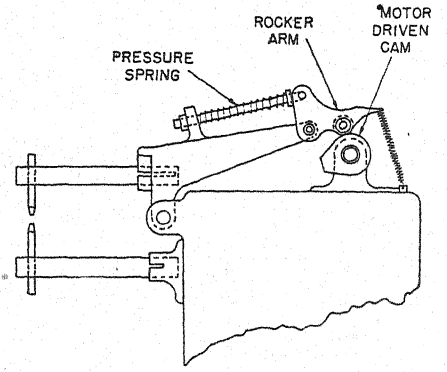


Fig. 23—Mechanically Operated Rocker Arm Spot Welder

In this pressure system operated by a cam the adjustment of pressure values is the same as on the manual type, that is, the adjusting of the spring compression. However, with the mechanical system, considerably higher pressures are obtainable.

Air-Operated Press Type Welders.—Press type welders are used for applications requiring high pressures for spot and projection welding. This press type design permits a straight line vertical movement of movable electrode assembly.

The direct air-operated press type welder employs one of the simplest pressure-applying mechanisms which affords higher pressures and automatic operation. In the direct air-operated type the movement of the electrodes in and out of engagement and the pressure applied to the weld are both obtained from the same source which is an air cylinder fed from a compressed air source.

The air pressure system of this type of welder is shown in Fig. 24. This sketch shows a double-acting cylinder, the movement of the piston of which is controlled by a multiport valve. The operation of this valve, which may be manual or automatic, alternately lowers the electrode assembly applying pressure to the work being welded, and then disengages the electrodes and retracts the assembly.

The air pressure applied to the top of the piston furnishing the pressure on the work being welded is adjustable in magnitude by the pressure regulator installed in the air supply line.

The magnitude of the air pressure applied to the piston top is indicated by the gage between the air cylinder and the regulator. The total pressure applied to the electrode assembly can, therefore, be calculated if the diameter of the piston is known.

Figure 24 indicates that the pressure applied to the underside of the piston in retracting the electrode assembly is the full line pressure.

This provides rapid retraction of the movable electrode assembly. In order to obtain a maximum of electrode life, prevent shock to the welder parts and reduce deformation of parts being welded, it is necessary to avoid a hard impact when the electrodes engage the work.

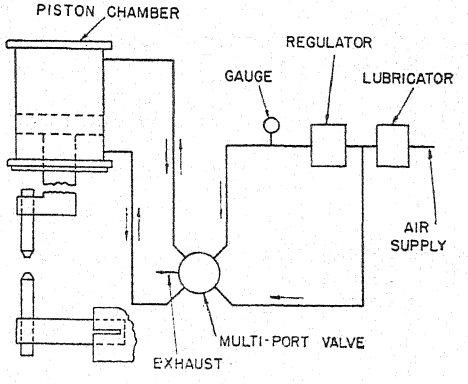


Fig. 24—Pressure System for Air-Operated Welder

In an air-operated mechanism it is, therefore, highly desirable to restrict the speed and cushion the movement of the piston.

To obtain this effect, air cylinders are equipped with speed control valves and air cushions, the essential features of which are illustrated in Fig. 25.

Air Cushions and Speed Control Valves.—Cushions may be provided at either or both ends of double-acting cylinders. The purpose of these cushions is to retard or cushion the piston at the end of its stroke. Figure 25 illustrates the operation of the cushion. Assume the piston to be in the "up" position, as shown, with the portion of the cylinder below the piston open to exhaust and air admitted above the piston through the action of the 4-way valve. Air pressure will be built up in the upper chamber. As soon as this pressure overcomes the static pressure, the piston starts moving downward as fast as air can be supplied by the pipe lines to maintain the necessary pressure. During this movement, pressure on top of the piston will not be the predetermined regulator pressure, but a lesser pressure. The exhaust air passes through the cushion chamber *B*, to the exhaust line *C*. As soon as the piston extension *A* enters the cushion chamber *B* (which is a very close fit), the exhaust air is trapped in the lower chamber. The air must then escape through the port *D* and needle valve *E*, and from there to the cushion chamber to the exhaust port *C*.

The action of the needle valve in limiting the escape of the exhaust air builds up a pressure in the exhaust chamber, slowing up the movement of the piston, while pressure in the upper, or admission chamber, is building up to the predetermined regulator pressure. By adjusting the needle valve at *F* this retarding action may be controlled. On the return stroke of the piston, *C* becomes the intake port and *G*, the exhaust port. In this case the cushion is by-passed by the check valve *H*, permitting full speed return.

An essential factor in the adjustment of the electrodes on a welder equipped with this type of air cushion is that the electrodes must not engage the work prior to the seating of the pressure piston in the air cushion.

Speed control valves also shown in Fig. 25 perform essentially the same function as the cushion, and the principle of operation is the same. Exhaust air must pass through the needle valve *L* into the exhaust line. On the down stroke the needle valve is by-passed by the ball check valve *M*. It will be noted in this case that cushioning takes effect throughout the upstroke of the piston.

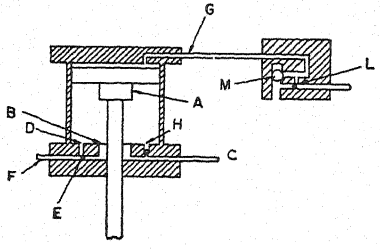


Fig. 25—Air Control Valves

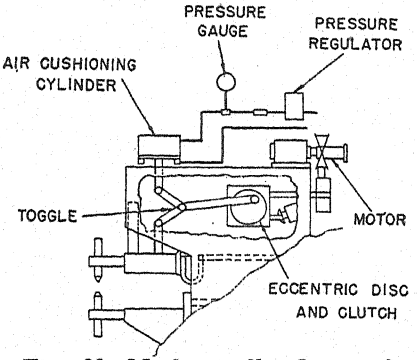


Fig. 26—Mechanically Operated Welder with Air Pressure System

The flexibility of an air operated system can be seen from the many combinations of cushion and speed control valves which can be connected on either side of the piston.

In air-operated cylinders an appreciable time may be required for the pressure to build up to its maximum value on the electrodes, due to the time element involved in moving the piston and rate of air flowing into the cylinder. It is very necessary to recognize this lagging effect in adjusting certain types of weld current initiating devices to insure that full pressure is applied to the work before the welding current is initiated. Operating data for air cylinder operation are listed in Table 1.

Combination of Mechanical and Air Mechanisms.—An example of a press type welder employing two sources of pressure operation is shown in Fig. 26.

In operation, the disc and toggle arrangement allows the upper electrode to travel rapidly from open to closed position, with a minimum of impact. When the toggle links are in line with the electrode and piston, the piston

Table 1

Air Cylinder Diam., In.	Area, Sq. In. (*a*)	Direct Pressure, 80 Lb. Air (*b*)	Air Consumption, Cu. Ft. Free Air per In. Stroke (*c*)	Size Valve Required, In. (*d*)
2	3.14	251	0.0115	1/4
2 1/2	4.91	393	0.0179	1/4
3	7.06	565	0.0258	1/4
3 1/2	9.65	771	0.0353	3/8
4	12.58	1000	0.046	3/8
4 1/2	15.9	1270	0.058	3/8
5	19.64	1570	0.0725	3/8
6	28.27	2260	0.103	1/2
7	38.48	3080	0.14	1/2
8	50.26	4020	0.184	3/4
9	63.62	5100	0.232	3/4
10	78.54	6280	0.288	3/4
12	113.00	9050	0.415	1
14	154.00	12300	0.565	1

(*a*) This is also the volume in cubic inches of the cylinder per inch of stroke.

(*b*) This is theoretical pressure, without taking account of packing or other friction or pull back springs.

(*c*) Compressed air is measured in terms of free air, which is zero pounds gage, 15 lb. absolute, or 1 atmosphere. Col. (*c*) is based on 80-lb. gage or 6.33 atmosphere. For other pressures, convert the gage pressure to absolute pressure (by adding 15 lb.) then figure the volume in direct proportion to the pressure.

The figures in col. (*c*) are based on single-acting cylinders. For double-acting cylinders, double the amounts shown. On adjustable stroke cylinders, only the actual amount of the stroke need be figured. Where full stroke is limited by interference, such as points contacting, figure the actual movement in the forward motion and the full rated stroke in the reverse direction. The figures do not include loss by leakage, or that consumed by hose lines and in valves. This can be estimated at 10 to 50% additional, depending on the location of the air valve.

The cost of compressed air may be estimated at 10¢ per thousand cubic feet if the exact cost is not known.

(*d*) This is the size of the cylinder pipe connections. Valves and intermediate connecting lines should be this size. For extra high-speed operation, larger lines may be used.

moves slightly away from its seat and exerts a force on the electrode, in addition to the weight of the electrode and carriage.

This provides a positive means of pressure application with a minimum of impact, even though the speed of the electrode closing and opening is rapid. The force applied to the electrodes is readily calculated from the regulated line pressure and the area of the piston as previously mentioned. In all pressure calculations, it is necessary to consider the weight of the moving electrode assembly which should be added to the applied force to give the accurate force total on the electrodes.

In the air pressure system shown in Fig. 26 there is no air consumption, except what little may escape around the piston. Other types of press welders employ a mechanical motor-driven cam mounted directly over the line of travel of the upper quill. This cam, in turning over, may compress a spring or the air in a cylinder which in turn exerts a force upon the electrodes and work. This type of mechanism is shown in the sketch Fig. 27.

Hydraulic Pressure Systems.—In modern automatic spot- and projection-

welding equipment, particularly in specially constructed high-speed welders, the hydraulic system of pressure application is widely used.

This hydraulic-operated mechanism is commonly called multimatic or hydromatic welding where a multiplicity of electrodes and transformers may be used. This type of equipment is usually a single purpose machine and may have from two to as many as 100 or more spot welding stations arranged in a manner to weld a complex assembly.

The hydraulic cylinders have the electrodes mounted directly on their piston rods and are usually controlled by rotary or linear travel valves which operate one or more welding stations in sequence.

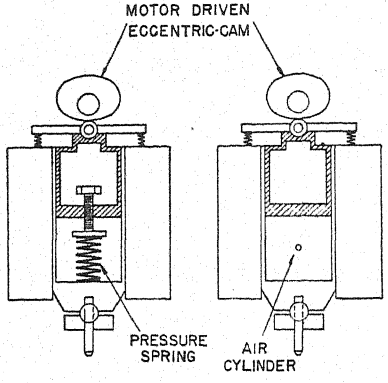


Fig. 27—Mechanically Operated Spring and Air Pressure Heads

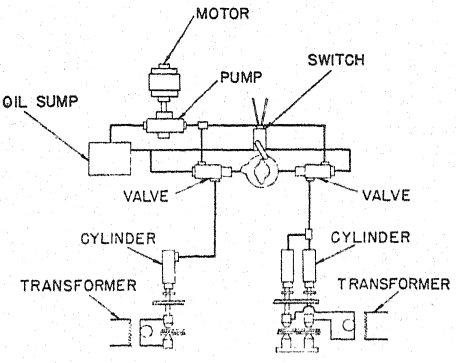


Fig. 28—Hydraulic Pressure System

Figure 28 shows the elementary components of a hydraulic pressure system connected to a two-station welder. This hydraulic system of pressure application permits high-speed operation and accurately sequenced welding cycles.

Variable-Pressure Cycle Systems.—In some types of spot-welding machines both the conventional a.c. type and the stored energy type system for varying the welding pressure during predetermined periods of the welding cycle are employed.

One system being extensively employed on a stored energy type spot welder particularly for use in welding the light metals and alloys follows the sequence—first, a high initial pressure is applied to the work to establish good electrical contact between the work and the electrodes; second, the pressure is decreased automatically an instant before the peak welding current to obtain a higher contact resistance and prevent mechanical collapse at the point of the weld; third, immediately after the current peak the pressure is increased to a high value, possibly greater than the yield point of the metal being welded.

This latter recompression period or forging pressure permits a lower pressure during current flow, than would be used to prevent weld cracking in a single pressure system. The high forging pressure tends to mechanically work the weld metal thereby increasing the strength and ductility of the welded parts.

The magnitude of these pressures may be varied over a wide range for various gages and various materials.

The forging welder or hammer type spot welder employs a variable pressure cycle in conjunction with pulsation welding of heavier steel stock.

While the welding current is being periodically interrupted the welding pressures are increased and decreased in rapidly repeating action, the effect being to "hammer" forge the weld.

Selection of Pressures in Spot and Projection Welding

General Considerations.—The optimum pressure required to satisfactorily weld two materials together depends upon several factors:

1. The metallurgical characteristics of the metals or alloys.
2. The physical state or temper of the material.
3. The thickness of the stock.
4. The surface condition.

On some materials, such as cold rolled steel, the allowable range of pressures is rather wide.

On other materials, such as aluminum and its alloys requiring close duplication of conditions for each weld, the pressure range may be quite narrow. The pressure applied to the electrodes should preferably not exceed the yield point of the electrode material, otherwise the electrode face will mushroom too rapidly under pressure, resulting in a decrease in the unit pressure and current density in the weld area during welding. Extremely high-electrode pressures will necessitate frequent dressing of the electrodes to restore their original shape.

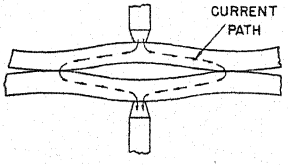


Fig.—29 Insufficient Pressure on Buckled Sheet

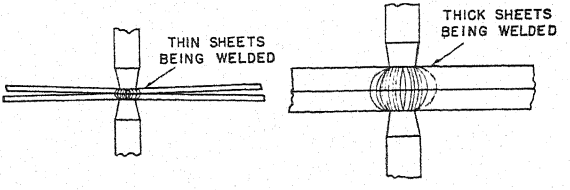


Fig. 30—Current Distribution in Thin and Thick Sheets

Pressures sufficiently high to cause appreciable deformation of the welded members and skidding of the electrodes should be avoided.

When insufficient pressure is applied the welding current may not be sufficiently concentrated in the weld area, as shown in Fig. 29, which illustrates an exaggerated condition. In spot welding thick sheets, the welding current spreads over a large area because the thicker the two sheets, the more the total pressure will distribute itself over the surface of contact of the two sheets without being concentrated in a definite spot.

Figure 30 shows the effect of pressure and current distribution on thin and thick sheets. The slight deformation in the thin sheet tends to concentrate the welding current in the area to be welded.

Pressures for Spot Welding Low Carbon Steel.—In many cases it will be found that the most suitable pressure for welding cold rolled steel will be dictated by the geometry of the parts to be joined and the nature of the specific application.

These pressures are based on a unit pressure of 14,000 psi. on the electrode face. For cold rolled steel stock, up to $^{3}/_{16}$ in. thick, unit pressures of from 12,000 to 18,000 psi. have been found satisfactory in spot welding.

In welding scaly steel the pressure should be 18,000 to 30,000 psi. It may be stated generally that the pressure should be increased with shorter weld time because short current timing necessitates a higher current density. (See Chapter 9.)

FUNCTIONS OF SEQUENCE CONTROL

Hydraulically operated or air-operated machines controlled from a manually actuated valve require only the more simple timing devices already described. Operation is said to be *semi*-automatic to the extent that the timer causes the power circuit to be opened at a definite interval after it is closed. Additional functions associated with the control of electrode motion must be performed by other means.

An air-operated machine equipped with a solenoid-operated air valve can be made to be fully automatic if the proper control device is selected for that purpose. An automatic weld timer controls both the duration of current flow through the work piece as well as the order and duration of the several pressure events occurring during the complete resistance-welding cycle. This also applies to hydraulically operated machines.

A sequence timer is a device for automatically controlling only the order and duration of the several pressure events occurring during the resistance-welding cycle. Control of the weld time is not included; therefore, must be performed by some other means.

The various periods to be controlled in both weld and sequence timers are defined below:

SQUEEZE TIME: The time from application of pressure to the electrode actuating means, until application of welding current.

Its purpose is to insure that sufficient welding pressure is on the work before power is applied. A pressure switch can be used instead of a time delay period. The use of both squeeze period timer and pressure switch in some instances would provide all desired control elements.

WELD TIME: The time that the welding current is applied to the work piece in making a single weld.

This function would be automatically accomplished in a weld timer but would be omitted in a sequence timer.

WELD INTERVAL: The total heat and cool times (or the total welding period) when welding by the pulsation method.

HEAT TIME: The time that welding current flows between interrupted periods when welding by the pulsation method.

This interval would be automatically controlled in a weld timer but would be omitted from a sequence timer.

COOL TIME: The time that the welding current is interrupted when welding by the pulsation method.

HOLD TIME: The time that pressure is maintained at the electrodes after the current is off.

Early welding machines were more sluggish in operation and the electrodes naturally remained on the work surfaces a considerable period of time after power was off, although solenoid valve and welding contactor were de-energized at the same instant. Since operating rates have been increased it is not uncommon for electrodes to part before the weld has properly cooled. The hold period is included to make possible the keeping of pressure on the work a suitable period of time after power is off. This procedure prevents fracture of the weld if the metal is under stress and also allows the water-cooled electrodes to conduct away surplus heat as it comes to the surface, thereby reducing discoloration immediately adjacent to the weld area.

OFF TIME: The time (in repeat welding) that the electrodes are separated from the work piece.

This interval gives the operator time to move the work or the welding tool to a new position before the cycle of operation is repeated.

Both sequence and weld timers are built from non-synchronous timing devices and high-speed control relays interconnected to provide the operating functions necessary to the application. Any one of the several types of timer mechanisms previously described can be used for this purpose.

A wide variety of timers is available, depending upon the number of periods to be controlled. The National Electrical Manufacturers' Association has assigned type numbers to the various standard arrangements. See Table 2.

Table 2

KIND	N.E.M.A. TYPE	PERIODS CONTROLLED
Semi-automatic weld timer	1A	Weld
Semi-automatic pulsation weld timer	1B	Weld interval, heat, cool
Automatic non-repeat weld timer	2A	Weld, hold
	2B	Squeeze, weld, hold
Automatic repeat weld timer	3A	Weld, hold, off
	3B	Squeeze, weld, hold, off
Automatic non-repeat pulsation weld timer	4A	Weld interval, heat, cool, hold
	4B	Squeeze, weld interval, heat, cool, hold
Automatic repeat pulsation weld timer	5A	Weld interval, heat, cool, hold, off
	5B	Squeeze, weld interval, heat, cool, hold, off
Automatic non-repeat sequence timer	6A	Hold
	6B	Squeeze, hold
Automatic repeat sequence timer	7A	Hold, off
	7B	Squeeze, hold, off
Automatic non-repeat pulsation sequence timer	8A	Weld interval, cool, hold
	8B	Squeeze, weld interval, cool, hold
Automatic repeat pulsation sequence timer	9A	Weld interval, cool, hold, off
	9B	Squeeze, weld interval, cool, hold, off

Non-beat is the term applied to a method of connection that causes the welding cycle to be carried through to completion, once it has been initiated, regardless of whether the pilot switch remains closed or not. This is accomplished by means of a maintaining circuit around the pilot device which is formed by the closing of a control relay at the time the cycle is initiated. Thus, the operator can release the initiating switch without danger of interrupting the automatic cycle.

A transformer having a 24-volt secondary that supplies power for the operating coil of an initiating relay is frequently a part of the control panel. This arrangement provides a low-voltage circuit for the initiating switch and thus protects the operator against danger of electrical shock, should the insulation of that switch fail.

Figure 31 illustrates a typical circuit for a Type 3B automatic weld timer. Means for controlling the squeeze, weld, hold and off periods are included. Closing the pilot circuit immediately energizes low-voltage

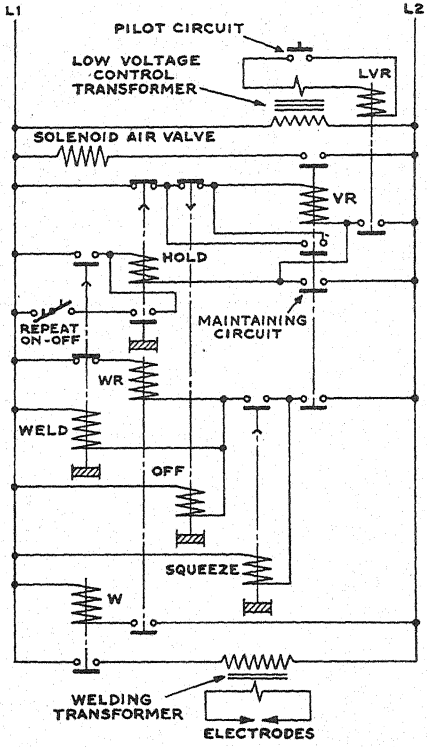


Fig. 31—Type 3B Automatic Weld Timer Controlling "Squeeze," "Weld," "Hold" and "Off" Periods

relay (*LVR*). It establishes a circuit to the operating coil of relay (*VR*) which in closing forms a maintaining circuit around the pilot device and also energizes the solenoid air valve, applying pressure to the welding tool. Another contact on relay (*VR*) energizes the operating coil of the squeeze period timer. After an interval allotted for building up pressure on the work, its contacts close, energizing the weld and off period timers, as well as control relay (*WR*). Relay (*WR*) energizes the welding contactor (*W*), which applies power to the welding transformer. After an interval equal to the setting of the weld period timer, its contacts are operated to disconnect control relay (*WR*) and energize the hold period timer.

Operation of the hold timer disengages relay (*VR*) disconnecting the solenoid valve as well as releasing the off period timer. After a predeter-

mined interval, the off timer contacts close, permitting re-energization of relay (*VR*). Thus the cycle of operation is repeated until the initiating switch is released.

Closing the repeat switch contacts in series with the normally open contact of the hold timer provides a holding circuit when that timer is operated and prevents repeat action.

Controls for Energy Storage Welding

Energy storage spot welding is accomplished by electrically storing the proper amount of energy and then quickly discharging this energy through a welding transformer to produce the weld. No weld timing device as such is required since the electrical constants of the storage and discharge circuits themselves provide control over both time and magnitude of welding current. Over certain practical limits these constants may be made adjustable, and through such adjustment a given amount of energy may be released with either very high current during very short time or with relatively lower current and correspondingly longer time. The time duration of substantial welding current is from approximately 0.005 to 0.05 second in present practice. Welding current peak magnitudes are often as high as 50,000 amp. and may be several times this amount.

Energy storage welding is, therefore, characterized by its application of heavy current for relatively short time without the usual high kva. demand on the supply source. Direct-connected a.c. welding equipment might, for instance, demand 350 to 400 kva. low-power factor single-phase line loading to produce a given weld in aluminum alloy. This same weld can be produced with energy storage equipment demanding a maximum of only 50 kva. high-power factor three-phase line loading. In addition storage equipments are generally designed to store a substantially unaltered amount of energy regardless of $\pm 10\%$ change in line voltage. The welding speed will, however, be limited because of the time required to store the necessary energy. In this assumed case the maximum welding speed might be limited to 60 welds each minute, while the a.c. equipment will not necessarily be so limited. Further continuing this particular comparison, the energy storage equipment itself is appreciably more costly than the a.c. equipment. However, the a.c. equipment may require the installation of stable voltage and costly supply line equipment which in some cases more than offsets welding equipment cost.

The welding current delivered by energy storage equipment is generally in the form of a single uni-directional pulse applying heat to the weld continuously throughout the time of its formation. Also, as mentioned previously, the current is high and the time short. Such short timing tends to localize welding heat to the immediate weld region. This type of welding has, therefore, been found particularly useful for the class of metals and alloys which have high electrical and heat conductivity and sharp fusion point. It has also been found useful for the welding of stainless steel and for ordinary steel which requires short timing and a high degree of precision. The principal present use is for strong aluminum alloy and also stainless steel welding in aircraft manufacture.

Complete control equipment for energy storage welding includes an

energy storage reservoir together with adjustable charging and discharging apparatus. It also includes the usual electrode pressure and sequence control devices common to all types of resistance welding.

Energy storage welding control equipments are of two general types, the electromagnetic and the electrostatic, as follows from the system of energy storage used in each. These two types are described in Chapter 9.

MEASUREMENT CONTROLS

Current is an essential factor in the complete specifications of spot-welding conditions. Therefore, the need for the measurement of spot-welding current arises, if optimum conditions determined in experimental laboratories are to be duplicated in production shops. Laboratory methods must be accurate and supplemented by facilities for ready calibration into secondary amperes. Shop methods must be convenient; reasonably accurate and free from the possibility of accidental error. Shops find current measurement of great value in resetting welding machines for conditions which have previously been found satisfactory.

The problem is complicated by several factors, chief of which is the duration of current flow, which is commonly of the order of one-tenth second, but may be more or less. Another factor is the variable transient current produced by non-synchronous closure of welding circuit. A third factor is the wave shape of the welding current. Methods which depend upon the peak value of the current, or the rate of change of the current as it passes through its zero value, will be satisfactory for sinusoidal current waves. However, such methods will be of no value with wave shapes such as are produced by phase control of the firing of mercury-vapor tubes, or the wave shapes of stored-energy discharges.

Figure 32 illustrates the various methods of measuring spot-welding current. The solid lines connecting the instrument to the welding circuit indicate one method of connection, and the dotted lines indicate an alternative method of connection.

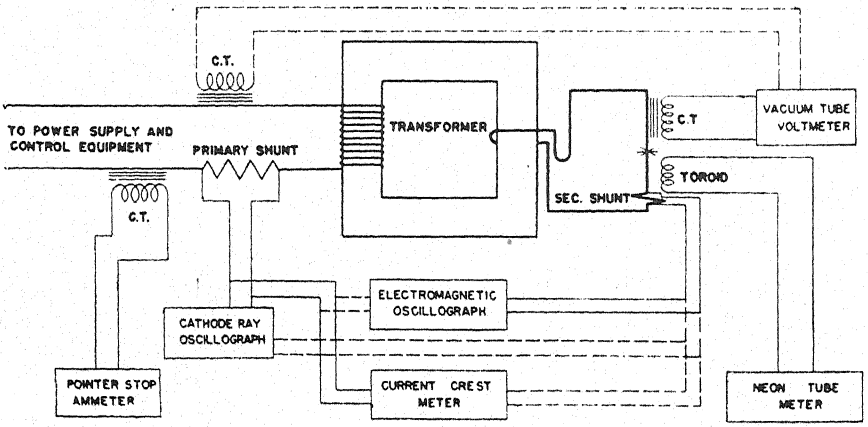


Fig. 32—Various Methods of Measuring Spot-Welding Currents

Secondary Amperes

The methods which may be used to measure the current in the secondary circuit are the following:

1. Secondary shunt, used with either an electromagnetic oscillograph, a cathode ray oscillograph or a current-crest meter.
2. Current transformer, slipped over the arms of the secondary circuit or over one of the electrodes and connected to a vacuum-tube voltmeter.
3. Toroid, slipped over one of the electrodes and connected to a neon-tube meter.

The first method above, when used with an electromagnetic oscillograph will give not only the magnitude of the current but also its wave form. This method is, therefore, the most versatile of all the current measurements. It is, of course, not a method to be used in the shop for setting up machines but a method of studying resistance welding in the laboratory. The method is, however, not only useful with alternating-current waves with or without transients, but also for stored-energy discharges, where the wave form is essential in evaluating the current. An oscillograph is suitable for evaluating the steepness of the wave front, the peak value of current and the heating effect. The second method above depends upon reading the peak value of the current and is, therefore, of value only with sinusoidal current containing no transients. A modification of this method, which slows the charging of the condenser in the vacuum-tube voltmeter during the first few cycles, thus reading the peak value of the later half cycles of welding current, makes the correct reading of the heating value to be more closely approached. Thus if a current of 15 cycles duration has a transient existing during the first three or four cycles, the meter would give a more representative value by reading the value of the last ten cycles rather than the first one or two. Such a meter would be of very little use in evaluating a stored-energy discharge, since it could only measure the peak value of such a current. Such a method is also inapplicable to the wave forms which are produced by phase-control of the discharge of mercury-vapor tubes.

The toroid and neon-tube meter depend for their reading upon the peak value of the voltage induced in a toroid, which is proportional to the maximum rate of change of the secondary current. Such a meter is also of value only in the measurement of sinusoidal currents without transients.

Electromagnetic Oscillograph-Secondary Shunt.—The shunt used with this method is a hollow cylinder of manganin built into one of the water-cooled electrode holders, by means of double male-threaded construction. Potential connections in the shunt are of the knife-edge type usually employed for the precise determination of low resistance in the Kelvin double bridge. The potential connections are usually mounted on an insulating block so that the distance between them may be accurately measured. The resistivity of the manganin is determined by the maker of the shunt so that a calibration value for the shunt and potential connections is supplied with the equipment. Coaxial conductors carry the potential connections away from the shunt in a direction perpendicular to the electrodes and parallel to the plane of the secondary loop. Care must be taken in the manufacture of the potential connections to avoid the introduction of vertical loops in the circuit. The effectiveness of these precautions to eliminate induced

voltage from the circuit should be checked experimentally. This may be accomplished by taking an oscillogram during the passage of welding current, with the oscillograph connected to the potential circuit which is short-circuited and insulated from the shunt.

The simplicity, directness and precision of the calibration involved in the secondary shunt make this method a standard of comparison for other methods. With the conventional a.c. resistance-welding equipment, if current is the only measurement desired, a simpler method than the use of the secondary shunt can be used. However, no other method will be so precise in the measurement of transient currents, or the currents resulting from stored-energy discharges. A very important use of the secondary shunt and electromagnetic oscillograph has been in the study of resistance changes during the making of actual welds. The energy required in spot welds may be calculated from the results of these same measurements. The measurements involve simultaneous determinations of the voltage drops in the parts of the circuit being investigated, and current measurement with the shunt.

Cathode-Ray Oscillograph—Secondary Shunt.—If a secondary shunt is available in a welding machine, it is sometimes convenient to use a cathode-ray oscillograph as a means of measuring the crest value of the current. However, the principle object of such a connection will be for the purpose of observing the wave form, to see that it is sinusoidal, or that both tubes are properly firing in case the switching of the welding circuit is being performed by mercury-vapor discharge tubes. By means of a long-persistance screen, it is possible to observe the wave forms of stored-energy discharges. This arrangement avoids a great deal of photographic work. If it is desired to calibrate the cathode-ray oscillograph as a current crest meter, it will be necessary to provide a calibration circuit which may be easily and frequently used for adjusting the amplifier gain to bring the meter into calibration. A simple circuit, using a voltmeter, a variable alternating voltage and voltage divider, may be set up permanently to accomplish the above calibration easily and as frequently as desired. A cathode-ray oscillograph is frequently available in a welding laboratory for checking wave forms, transient conditions and phase-control settings, so that the possibility of using this instrument for current measurement may prove desirable.

A word of caution regarding the use of a cathode-ray oscillograph for current measurement is necessary because of the fact that these instruments are frequently affected by the magnetic field of the welding current. This difficulty may usually be overcome by placing the instrument at a reasonable distance from the welding machine and by turning it in a proper direction to minimize the disturbance. Some of the newer cathode-ray oscillographs are available with magnetic shielding of the tube which is a great advantage for welding current measurements.

Current-Crest Meter—Secondary Shunt.—This method of measurement uses an electromagnetic-oscillograph element to measure the drop in potential across a shunt in the welding circuit. The oscillograph deflects a light beam upon a translucent scale usually graduated in millimeter divisions. No attempt is made to sweep the light beam across the screen and introduce a time axis. The reading of the meter consists of observing the amplitude of the deflection of the spot of light during the passage of the

welding current. If the wave form of the latter is sinusoidal, the effective value of the current may be calculated by well-known relations. With a little practice an observer may easily read these deflections to a half millimeter, and thus determine the welding current with an error of not over 2%. These readings are most easily taken when synchronous closure of the circuit avoids the introduction of transients. If transients do appear, the magnitude may be observed. Readings may be taken by this method even if the time current flow is only one or two cycles. The pointer has such low inertia that there is no problem of rapid response such as provides difficulty with an ordinary ammeter, and even with the pointer-stop ammeter. An instrument of this type has been developed rather recently, for installation on a control panel, or for ordinary portable use on a table. If an ordinary portable oscillograph is available, one of the elements may be used for this type of measurement. All of the methods so far discussed, which involve the use of a secondary shunt, are limited to laboratory study, because of the necessity of having a shunt built into the electrode holder which is not a practical condition for general use in the shop. In order to avoid the necessity of using a built-in secondary shunt the other methods of measuring secondary current, outlined above, have been developed.

Vacuum-Tube Voltmeter.—A vacuum-tube voltmeter may be used to measure welding current in terms of the drop of potential across a shunt connected in a series with the secondary circuit of a current transformer. The current transformer used with this instrument is designed for use in the secondary circuit by slipping the transformer over the electrode holder. Figure 33 shows the fundamental vacuum-tube voltmeter circuit. The basic principle involved in the method is illustrated in Fig. 33-A. The voltage drop, E_1, across the shunt on the current transformer charges the

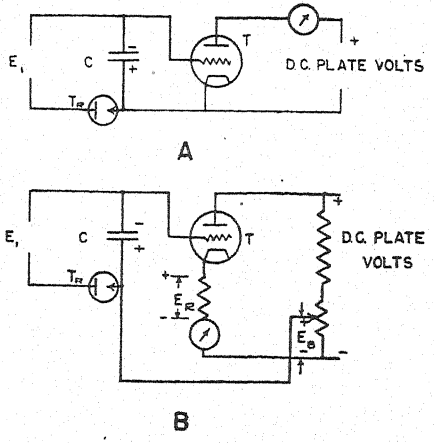


Fig. 33—Fundamental Vacuum-Tube Voltmeter Circuit

capacitor C through a rectifying tube T_R. This causes the grid of the tube to become more negative thus reducing the plate current. The capacitor is required to retain its charge and thus maintain the reduced current for a sufficient time to permit reading. Figure 33-B illustrates a second

stage in the development of this meter. Two features of adjustability are provided in this circuit. The sliding contact with the indicated voltage drop, E_B, permits adjustment of the plate current to the desired top-scale value before each reading. The resistance associated with the drop, E_R, in the cathode lead, permits adjustment of the over-all sensitivity of the circuit.

One of the principal advantages of this instrument is that the readings are definite and may be obtained with one weld. Also, the secondary current may be measured directly. With circuit refinement to delay the charging of the capacitor the meter may be used to measure the welding currents with large transients existing during the first few cycles. Such transients are caused by non-synchronous closure of the welding circuit, and render inaccurate the measurement of current by almost all methods except the oscillographic.

The difficulties with the vacuum-tube voltmeter are associated with the current transformer and with the fact that it is a peak-reading instrument. The design of an iron-core current transformer to handle such heavy currents involves some sacrifice in portability. The introduction of so much iron into the secondary current loop affects somewhat the output of the welding machine. In the case of a machine with 12-in. throat depth the output was reduced about 3% when the current transformer was placed in position. This effect would, of course, have been very much less with a machine of larger throat area.

The fact that the vacuum-tube voltmeter is a peak-reading instrument means that it is not suitable for non-sinusoidal currents such as are caused by phase control of mercury-vapor tubes. It is also of very little use in evaluating stored-energy discharges. A further word of caution with regard to the use of the vacuum-tube voltmeter is that it must not be used with currents beyond its proper range because of the danger of saturating its current transformer which would result in serious error in the reading. Unless the current transformer is shielded magnetically, there is sometimes a difficulty experienced when the current transformer is slipped over the electrode, and rests against the electrode arm. The current in this arm may tend to saturate a portion of the iron core of the current transformer.

Neon-Tube Meter.—Neon-glow lamps may be employed as voltage indicators, making use of the fact that the break-down voltage is a definite value. For the measurement of welding current the neon tube is connected across a potentiometer circuit which is fed from a toroidal pickup coil. The air-core pickup coil is arranged to be placed around one of the electrodes of the welding machine. The voltage induced in this coil is applied across the potentiometer. In order to secure a method of exactly setting a neon tube to measure the toroid voltage, two neon glow lamps, having nearly the same critical voltage, are connected in parallel across the same points on the potentiometer. While successive welds are made, the potentiometer connections are progressively changed until the point is reached at which just one lamp glows. The magnitude of the secondary current in the welding machine is then obtained by referring to the meter calibration.

It is necessary to obtain a reading by means of several trials by repeatedly making welds under identical conditions. It is also necessary to calibrate

the meter by some other current measuring method. The neon tube circuit is illustrated in Fig. 34. Characteristics of such a circuit are shown in Fig. 35. A typical calibration curve for the neon tube meter is shown in Fig. 35-A. This calibration was obtained by making use of the electromagnetic oscillograph and secondary shunt as a standard means of current measurement. The voltage induced in the toroid is a direct measure of the secondary current, if it is sinusoidal. A voltage-current characteristic of the toroid is shown in Fig. 35-B which illustrates the straight line relationship between toroid voltage and secondary current.

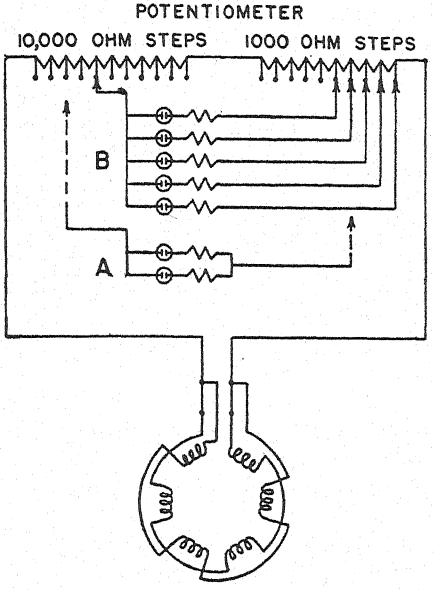


Fig. 34—Fundamental Neon-Tube Meter Circuit

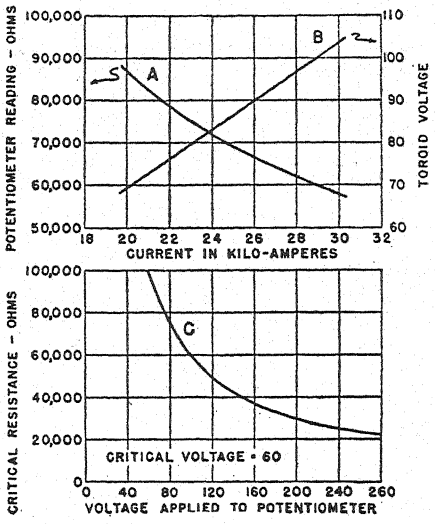


Fig. 35—Characteristics of Neon-Tube Meter Circuit

A—Meter calibration.
B—Toroid characteristic.
C—Potentiometer characteristic.

In order to obtain good sensitivity of current measurement, it is necessary that the toroid voltage be as close as possible to the critical voltage of the neon tube lamps. To accomplish this, the toroid is constructed of a number of separate pickup coils which may be connected in series for measuring low currents and in parallel for measuring high currents. The importance of having the toroid voltage not very much higher than the critical voltage of the neon glow lamps is evident from inspection of Fig. 35-C. The change in critical resistance for a given change in applied voltage becomes much greater as the applied voltage approaches the critical voltage of the lamps. The precision of reading the resistance corresponding to the welding current is increased by the presence of a high fixed value of resistance connected between the two variable potentiometers. This prevents the use of the meter for small fractions of the total toroid voltage, but these readings are of reduced sensitivity, as mentioned above, and

therefore should be avoided. A word of explanation as to the action of a toroid in measuring current may assist in understanding the proper field of application for such an instrument. When a toroidal coil is placed around a conductor carrying an alternating current, a portion of the magnetic field set up by the current will link with the coil and induce a voltage proportional at any instant to the rate of change of the current. The peak voltage which is indicated by the neon glow lamps is therefore a measurement of the maximum rate of change of current which occurs when a sinusoidal is passing through its zero value. Only for sinusoidal currents is the effective or heating value proportional to the maximum rate of change of the instantaneous value. Hence, only such currents will be correctly measured by the peak value of the voltage developed in a toroid coil.

A precaution that must be taken in the use of a toroid is that the voltage must be measured without drawing an appreciable current from the winding, since any current taken will tend to oppose the flux set up by the current, displacing it from within the toroid and causing the toroid voltage to drop. The reason for using neon tubes is obvious since they fulfill the requirement of drawing only a very slight current.

The neon tube meter may be used with a single tube instead of the two tubes shown in Fig. 34. This is because of the fact that these small neon tubes have a slightly different starting voltage for the two halves of the a.c. wave so that it is only necessary in making a setting of the instrument to select a value which causes one electrode to glow and not the other. This accomplishes the same result as causing one tube to glow but not the other, when using two lamps, and there may be less confusion in watching only one lamp.

The primary advantage of the neon tube meter is its simplicity and low cost. When used simply as an indicator, it does not necessarily have to be calibrated. For example, after the optimum welding conditions have been established for a given job, the reading of the meter can be recorded and then used in checking when the job is set up again at a later date. The use of such a meter with non-synchronous timing will require greater care to obtain a reading since it will be necessary to make a greater number of welds in order to find the highest setting which will cause the neon lamp to glow for all welds. Every time a transient is produced there will be a more rapid rate of change of current and the neon tube will glow. The larger number of readings are necessary in order that some of the currents may be accidentally free from transients, and thus give a minimum voltage. Calibration and use of the meter require that the critical voltage of the lamps remain constant with time. Periodic calibration is advisable to insure that the lamp has not changed.

Primary Amperes

Because of the complication involved in placing a shunt or current transformer in the secondary circuit of a welding machine it is frequently desirable to measure the welding current by first measuring the primary current and then obtaining the welding current by calculation. All methods involving the measurement of primary current require the determination of the transformer ratio for all winding arrangements which are used. The transformer ratios are obtained by dividing the primary voltage by

open-circuit secondary voltages. It is also necessary to correct the total primary current for its magnetizing component, before calculating the secondary current. It is practical to measure the magnetizing current under open-circuit conditions and, in the case of the welding machine, to subtract this from the total primary current arithmetically rather than vectorially. This procedure is not much in error since the power factor is usually so low that the magnetizing and load components of the primary current are nearly in phase. In many cases the magnetizing currents will be so small that they can be neglected, but this should never be done unless tests have shown it to be true. If transformers are over excited or improperly designed, the magnetizing currents may be large. In measuring the magnetizing currents the ammeter should be short circuited when the circuit is closed so as not to subject the ammeter to the large transient inrush current. Shortly after energizing the transformer, the short circuit may be removed and the magnetizing current read.

In determining transformer ratio by exciting the transformer and reading primary voltage and open-circuit secondary voltage, there may be an error if the transformer core is approaching saturation, as evidenced by relatively high magnetizing current. Such an error is due to primary leakage impedance. The voltage drop due to this impedance should be subtracted from primary voltage to obtain the primary voltage induced by the mutual flux. The latter voltage should be then divided by the secondary open-circuit voltage to obtain the true transformer ratio. Owing to the difficulty of measuring the separate primary leakage impedance another approach to the determination of transformer ratio is preferable. For those welding-machine connections which give rise to an appreciable magnetizing current at rated voltage, the primary and secondary voltage readings should be taken with primary voltage at such reduced value that it will avoid an excessive magnetizing current. The turn ratio may then be calculated from these readings without appreciable error.

It has been suggested that difficulty may be experienced in reading the low a.c. secondary voltages required in determining the transformer ratio. No difficulty in measuring these low alternating voltages should be experienced, if a good laboratory instrument is available. Instead of using the voltage method for determining transformer ratio, it is possible to use primary and secondary current transformers. However, this involves the use of costly equipment which is ordinarily not available, and the method would appear to involve at least as much chance for error in the two transformers and accompanying meters as should be expected with the voltage method.

It should be noted that in any resistance-welding installation, it should be possible to determine once and for all the transformer ratios for the various machines for all of their possible connections, and at the same time to determine the magnetizing currents for all of these connections. This information will be available for as long as the shop voltage remains unchanged. It is, therefore, desirable and worthwhile to take the necessary amount of time to establish these values which may be used in translating primary current into secondary or welding amperes.

The methods which may be used to measure the current in the secondary circuit are the following:

1. Primary shunt, used with either an electromagnetic oscillograph, a cathode ray oscillograph or a current-crest meter.
2. Current transformer, used with vacuum-tube voltmeter or pointer-stop ammeter.
3. Toroid or air-core transformer, connected to a neon tube meter, or other voltage indicating device.

Electromagnetic Oscillograph—Primary Shunt.—The use of a shunt in the primary circuit is simpler than the use of such a device in the secondary circuit. A shunt for use in the primary circuit may be purchased as a standard piece of apparatus, which is therefore easy to obtain. It may even be constructed without much difficulty and it is simple to calibrate and install. The use of a primary shunt does not involve so much precaution to avoid the pickup of induced voltages, as does the secondary shunt.

A word of caution should be given with regard to the safety of the operator when using a shunt in the primary circuit. Care should be taken to mount the shunt so that there should be no occasion to come in contact with it while the primary circuit is energized, and to bring out insulated potential connections.

The primary shunt has an advantage over the current transformer for oscillographic work since the wave form of the secondary current of the current transformer may be distorted by transients, produced when the welder primary is energized at the proper phase angle for the welding circuit. These transient effects may be reduced by careful adjustment of the phase angle of this circuit to coincide with the angle of the firing of the main power tubes. This adjustment would be an objectionable, added complication. It would be particularly objectionable in a machine devoted to experimental work, since every new setup and material produces a different phase angle in the secondary circuit of the welding machine.

Cathode-Ray Oscillograph—Primary Shunt.—A cathode-ray oscillograph may be used with equal facility with a primary shunt, as with the secondary shunt previously discussed. The same considerations apply to the use of the cathode-ray oscillograph with primary as with the secondary shunt and the choice between them lies in whether a secondary shunt is available or whether it seems preferable to install the primary shunt.

Current-Crest Meter—Primary Shunt.—The current-crest meter may be used with equal facility with either a primary or secondary shunt. The choice is the same as for the cathode-ray oscillograph just discussed.

Vacuum-Tube Voltmeter—Primary Current Transformer.—The vacuum-tube voltmeter which was previously discussed in connection with the use of a special current transformer, arranged to be slipped over one of the electrodes, may also be used with a current transformer in the primary circuit.

Pointer-Stop Ammeter—Current Transformer.—This instrument is commercially available together with calibrated leads and a clamp-on current transformer for use on the primary circuit. A diagram of connections to a welder circuit is shown in Fig. 36. The ammeter consists of an ordinary instrument to which has been added an adjustable stop which may be moved up behind the pointer. In measuring the short-duration spot-welding current, the pointer is gradually moved up the scale by adjusting the stop until the pointer just leaves the stop when a weld is made. An interval of travel of the pointer away from the stop of approximately

1/100 in. is allowed, which is about the minimum definitely perceptible. If the pointer does not leave the stop, it indicates that the setting is too high, whereas, if the pointer moves more than the minimum perceptible amount, the setting is too low. The action of the stop is thus to overcome the effect of inertia of the pointer. Thus the current will not have to move the pointer all the way up the scale but only a sufficient distance to indicate that the current is slightly greater than the value set by the stop. To determine the value of the current, it is necessary to make several welds under identical conditions in order to approach the correct setting of the stop for that value of welding current.

The great advantage of this instrument is the simplicity of reading and ease of attachment to the circuit. A further important advantage is that the method may be used to determine the effective value of phase-controlled currents which, of course, are not sinusoidal. In view of the increasing use of this type of welding current, the pointer-stop ammeter possesses an important element of superiority over devices depending for their reading upon either the peak value of current or maximum rate of change of current.

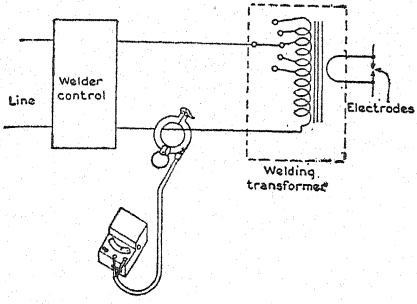


Fig. 36—Pointer-Stop Ammeter Connected to Welder Circuit

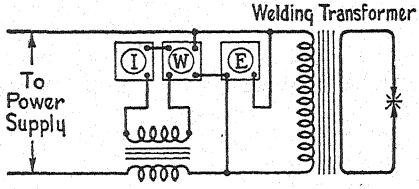


Fig. 37—Typical Connection for Use of Back-Stop Meters for Power Factor Measurement

There is a further practical advantage secured with the pointer-stop ammeter in that it is suitable for setting a welding machine to a particular value of current. It is only necessary to set the pointer by means of the adjustable stop, to the value desired and then to adjust the current control until the making of a weld causes the pointer to slightly leave the stop. Among the disadvantages of this type of meter are the errors resulting from non-synchronous circuit closure due to the transients produced, and the optimistic reading resulting from the double-frequency deflecting torque. This latter tendency is not necessarily fundamental in the instrument and later models may be expected to correct the tendency toward optimistic readings. It is also somewhat of an objection that the pointer-stop ammeter reading falls off when the time of current flow is three cycles or less. The amount of this falling off is not serious for the welding time of three cycles and amounts to only 4% in two cycles. Less significant disadvantages consist of those common to primary current measurements and which have already been discussed.

Neon-Tube Meter with Toroid.—It is, of course, possible to use the neon-tube meter in the primary circuit and the same transformer may be

used. The voltage induced in the toroid may be increased by passing the primary current through the toroid several times by means of a flexible cable. Care must be taken to insure that the voltage induced in the toroid is approximately of proper magnitude for good sensitivity. The toroid voltage for best sensitivity has already been discussed in connection with the use of the neon-tube meter in the secondary circuit.

Power Factor Measurement

The power factor of resistance-welding machines is considerably less than that of most other electrical apparatus. The low-power factor loads, resulting from increasing applications of resistance welding, is causing some concern to power engineers, plant engineers and others who are interested in the performance of power facilities. Power factor is an important item requiring consideration in determining the effects of a welder load on power facilities.

Most resistance-welder loads are intermittent and of short duration, ranging from one-half cycle to a few seconds. Because of the short duration of current flow, power factor measurements are more difficult to obtain on welding equipment than for most other types of equipment.

Power factor measurements may be taken by several methods. The method best suited for any given case will be influenced by the available measuring facilities, the accuracy required, and the conditions under which the measurements must be made. Before measurements are taken by any method, the machine should be arranged exactly as it is to be used in production. This applies especially to:

1. Throat depth.
2. Throat gap.
3. Type of work between electrodes.
4. Amount of work extending into throat.
5. Primary current tap—if the machine is equipped with a timer having phase shift heat control, it should be set at the maximum heat position.

Back-Stop Meter Method.—If the voltmeter, ammeter and wattmeter (Fig. 37) be provided with a suitable means for prepositioning the pointers, the time required for the pointer to become stable is greatly reduced. With meters so equipped, (or if the cover glass be removed from ordinary meters and suitable stops added) measurements may be taken during weld periods of the order of one-tenth second or less, depending on the amount of damping present in the meters. The correct reading is obtained when the movement of the pointer away from the stop is just perceptible. The accuracy of readings taken by this method will of course be influenced by any primary transients caused by non-synchronous closing of the primary circuit. If the timing is non-synchronous, the effect of transients can be minimized by employing a substantially longer weld period and observing the pointer position at the end of the period.

Typical connection for the use of back-stop meters for power factor measurement is illustrated in Fig. 37. Some judgment must be used in selecting the meters and the current transformer such that the values to be measured will lie within their accurate range. The back-stop meter is the most convenient method of making power factor measurements and is sufficiently accurate for most commercial requirements.

Power factor is the ratio of true power in watts to apparent power in volt amperes:

$$Pf = \frac{\text{Watts}}{\text{Volt amperes}} = \frac{\text{kw.}}{\text{kva.}}$$

Reduced Voltage Method.—If the primary voltage be substantially reduced, the secondary voltage and current will be reduced accordingly and the rate of heat generation between the electrodes will be reduced proportional to the square of the secondary current. Under these conditions the welding transformer can remain energized long enough to permit the pointers of ordinary meters to reach a steady position and the readings can be accurately taken. When the reduced voltage method is used, it will be necessary to disconnect, or short cut any timing apparatus which may normally be connected to the welding machine. Because of the abnormally low secondary voltage, it is essential that all secondary connections be clean and tight. This includes the work between the electrodes. The meter connections for this method are as shown in Fig. 37.

The power factor is expressed as the quotient of Watts/Volt amperes,

$$Pf = \frac{\text{kw.}}{\text{kva.}}$$

Magnetic-Oscillograph Method.—The magnetic oscillograph is perhaps the most precise method of making power factor measurements of resistance welding equipment and is the only satisfactory method for some conditions. This method is particularly suited for measurements where the weld period is less than one-tenth second, where the wave form is non-sinusoidal and where transients may be present. The oscillograph should preferably be equipped with a power measuring element. If a power measuring element is used, the power trace will be as illustrated in Fig. 38. The true power is

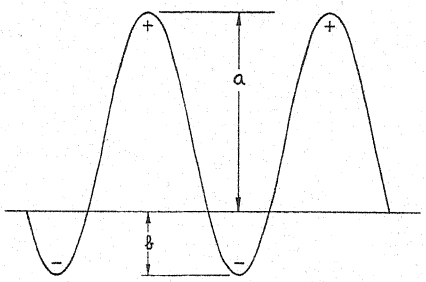


Fig. 38—Illustrating Power Trace Using Oscillograph Equipped with a Power-Measuring Element

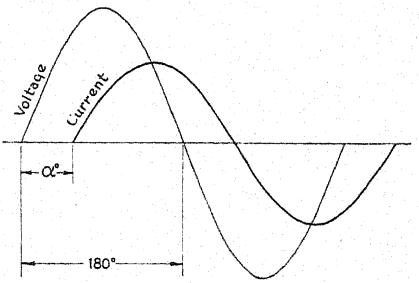


Fig. 39—Illustrating Current and Voltage Traces Using Oscillograph Without Power-Measuring Element

then the difference between the average values of the positive and negative loops and if the wave is sinusoidal,

$$\text{True Power} \quad \frac{a - b}{2}$$

and

$$\text{Apparent Power } \frac{a+b}{2}$$

$$\text{Power Factor } \frac{a-b}{a+b}$$

If no power measuring element is available, power factor measurements can be determined by the phase difference between the current trace and the voltage trace provided the oscillograph is operated at a high speed. The current and voltage traces are illustrated in Fig. 39. The phase difference is represented by α and is measured in degrees. The power factor is the cosine of the angle of phase difference.

$$Pf = \cos \alpha$$

Whenever the oscillograph method is employed, additional data can easily be recorded:

1. Duration of current flow.
2. Magnitude of voltage.
3. Magnitude of current.

Typical connections for oscillographic measurement of power factor are illustrated by Figs. 40 and 41.

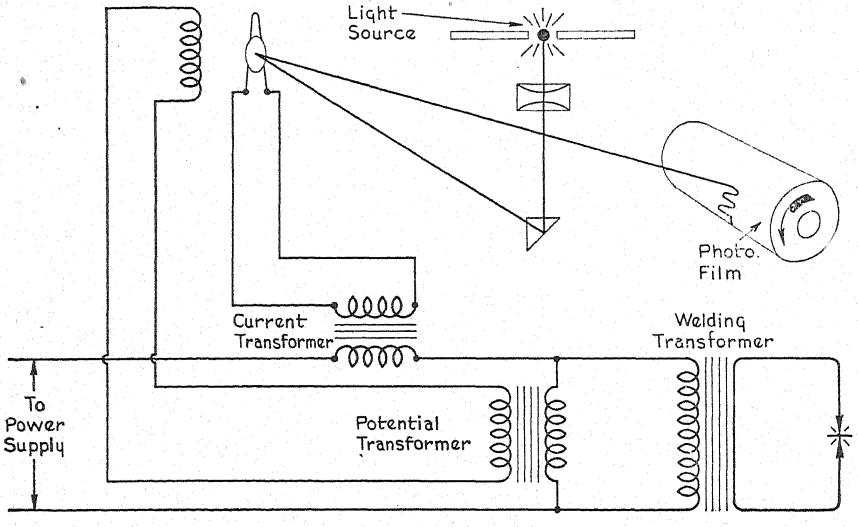


Fig. 40—Typical Connection for Oscillographic Measurement of Power Factor, Using Power Measuring Element

Impedance Measurement

The current which a resistance-welding machine may draw is determined by its impedance and the impressed primary voltage. Impedance must be

taken into account when specifying power and control facilities for a given machine and also when predicting the effect of a given machine on existing power facilities.

The impedance of a given machine is determined by the primary resistance and primary reactance, the secondary resistance and secondary reactance (Fig. 42). Combining the primary and secondary resistances and reactances and expressing them as total equivalent resistance (R) and total equivalent reactance (X) on the primary side (Fig. 43), the total equivalent impedance (Z) is expressed as:

$$Z = \sqrt{R^2 + X^2}$$

and from Ohm's law for a.c. circuits, $Z = E/I$.

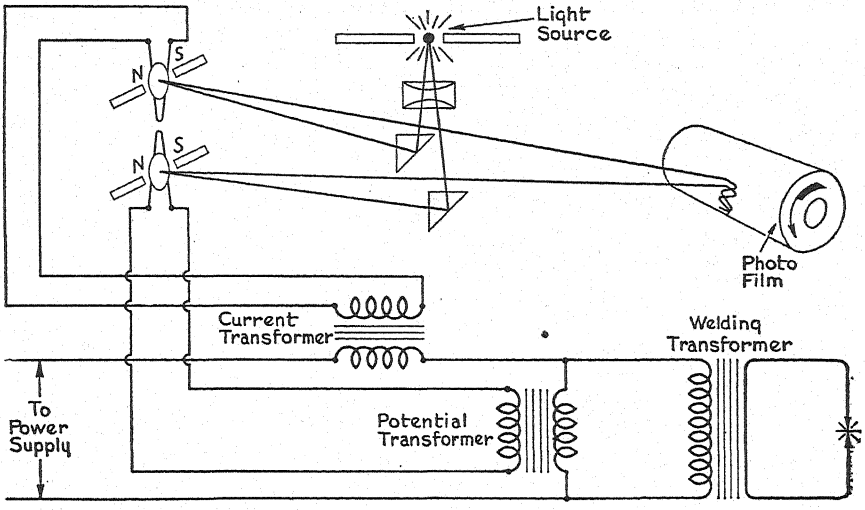


Fig. 41—Another Typical Connection for Oscillographic Measurement of Power Factor, Using Voltage and Current Measuring Elements

Since the total equivalent impedance is influenced by the character of both the primary and secondary circuits it will be necessary to arrange the machine to correspond to the desired circuit conditions before any impedance measurements are undertaken. The type of machine and purpose for which it is to be used should be considered before deciding upon the machine arrangement under which the measurements are to be taken. If the welder is a single-purpose machine used for one operation only it should be arranged to simulate production conditions as closely as possible. If it is a universal type machine having adjustable features and used for a variety of welding operations it should be arranged for maximum current conditions. Maximum current conditions are obtained when the throat depth, arm spacing and number of turns of the primary are a minimum. If the machine is equipped with a timer having phase shift heat control it should be set at the maximum heat position. The secondary circuit should be closed by the work to be welded or by a suitable shorting bar.

Impedance measurements like power-factor measurements can be made by several methods. Likewise the method best suited for a given case will be influenced by the available measuring facilities, the accuracy desired and the conditions under which the measurements are to be made, also the meters and instrument transformers must be selected such that the values to be measured will be within their accurate range. Usually impedance can be determined from measurements required for power factor determination.

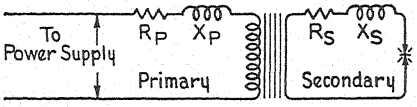


Fig. 42—Electric Circuit Properties Involved in Welding Machine Impedance

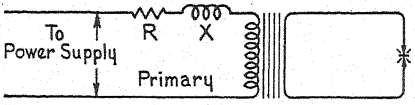


Fig. 43—Equivalent Circuit for Measurement of Impedance

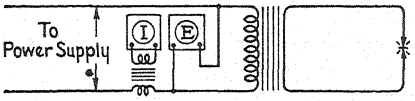


Fig. 44—Meter Connections for Back-Stop Meter Method or Reduced Voltage Method of Impedance Measurement

Back-Stop Meter Method.—If the volt meter and ammeter (Fig. 44) be provided with suitable stops for prepositioning the pointers, so that their movement is just perceptible, readings can be made during current flow periods of the order of one-tenth second. When the transformer primary is closed in a non-synchronous manner an error will be introduced by the inrush transient and will vary depending on the point on the voltage wave at which closure occurred and on the flux condition in the transformer core. When the circuit is closed in this manner a substantially larger current flow period should be employed and the meter readings should be observed at the end of the period. Typical connections for impedance measurement are as shown in Fig. 44. The back-stop meter method is the quickest and most convenient method of obtaining impedance measurements.

Reduced Voltage Method.—The most accurate impedance measurement can perhaps be obtained by the reduced voltage method. If the impressed primary voltage be reduced to the order of 10% of the rated voltage the welding transformer can usually remain energized for several seconds before any appreciable heating occurs in the secondary. Under these conditions the pointers of ordinary meters will have ample time to reach steady

state positions and the readings can be taken accurately. The meter connections for this method are the same as those shown in Fig. 44. Reduced voltage power can be obtained by the use of a suitable step-down transformer or by temporarily connecting the machine to a suitable low-voltage feeder. If the machine is equipped with an automatic timer it should be disconnected or made ineffective. Because of the abnormally low secondary voltage it will be necessary that all secondary contact surfaces be tight and clean. A suitable shorting bar should preferably be used to close the secondary circuit.

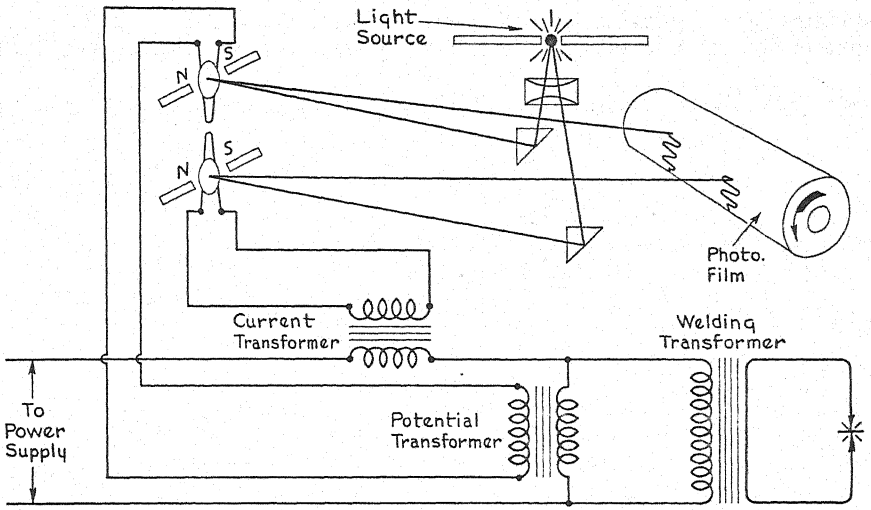


Fig. 45—Typical Oscillograph Connections for Impedance Measurement

Magnetic-Oscillograph Method.—The oscillograph method is usually not necessary except when large transients may be present, when the current flow period is less than one-tenth second, or when wave form data is also desired. Typical oscillograph connections are shown in Fig. 45. The voltage and current vibrator elements must be calibrated to give suitable deflection for the values to be measured, and the speed of the film regulated to give suitable spread if wave form data are required, before any measurements are undertaken. The magnitude of voltage and current is determined by measuring the amplitude of the voltage and current traces, respectively (Fig. 46).

Measurement of Time

The time of duration of current flow in resistance welding is an important factor in determining the consistency and quality of the welds produced. Most users of resistance-welding equipment rely upon the time calibration

furnished by the manufacturer of their timing equipment. If it is desired to check the accuracy of the timing of any equipment, three methods of time measurement are available:

1. The electromagnetic oscillograph.
2. The cycle counter.
3. The electrical impulse counter.

The electromagnetic oscillograph is, of course, the most accurate method for the measurement of time since it is possible to observe the actual wave shape of the 60-cycle current wave and count the number of cycles. In the case of stored-energy discharges, it is readily possible to place a timing wave of any convenient frequency upon the record for easy subsequent measurement. This timing wave may be an ordinary 60-cycle wave, or if greater accuracy is desired, a 1000-cycle per second wave may be used.

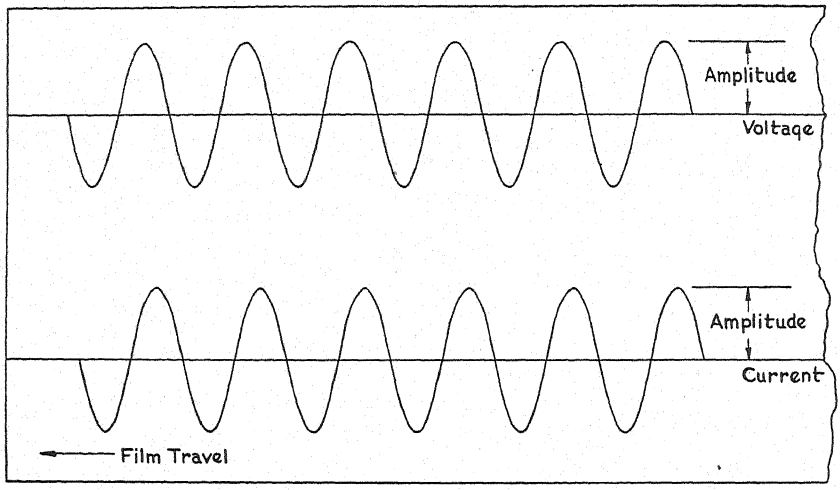


Fig. 46—Illustrating How Magnitude of Voltage and Current Can Be Determined by Measuring the Amplitude of the Voltage and Current Traces, Respectively

The cycle counter is an electromagnetic device containing a small pointer which presses against a strip of paper behind which is a carbon roll. The device receives impulses from the voltage applied to the welder and it is, of course, connected between the circuit device and the machine. The paper is driven by a small motor. The record consists of a small trace, approximately sinusoidal, which can be examined by the number of cycles counted.

The electrical impulse counter measures time by counting the half cycle pulses of an alternating-current wave. On a 60-cycle system it will count 120 pulses per second. It will thus count the number of half cycles from the beginning of the period of current flow to the completion of the weld. The wave being measured must have a voltage of approximately 18 volts.

The Measurement of Pressure

In the early application of resistance welding it was common practice to apply pressure by means of a series of weights acting either directly or through a lever system. Under these conditions pressure was considered to be determined by the magnitude of the weights, corrected if necessary by the ratio of the lever system. It was later realized that with such a mechanical system, the electrodes could follow any shrinkage of the weld section with only the moderate acceleration of gravity.

Due to recognition of the fact that high inertia tends to retard electrode follow-up, there has been a pronounced tendency in recent years toward the use of low-inertia systems. Air cylinders have replaced dead weight in the application of pressure. It has been common practice with air cylinders to calculate the electrode pressure from the dimensions of the piston and the internal air pressure.

Due to the presence of friction in the mechanical system, the determination of pressure by means of dead weight measurement or air cylinder calculation is in error by the amount of friction which is active. When the moving electrode comes down upon the work, there will generally be a reduction of pressure because of friction. Because of this fact it is preferable to measure the pressure at the electrodes by some sort of direct pressure measuring device.

In order to reduce the effects of friction in electrode pressure mechanisms, there has been introduced a series of devices, such as springs and rubber bellows. With these devices it is not possible to calculate the pressure, so some form of pressure measurement is necessary.

Several devices for the measurement of pressure have been used. One such device on the market depends for its reading upon the application of pressure to a metal diaphragm containing a fluid. The application of the electrode pressure to the diaphragm raises the fluid pressure which is read by means of a pressure gage. This pressure gage is calibrated in terms of actual pounds pressure of the electrode. Another pressure-measuring device which has been used consists of a U-shaped piece of metal acting as a sort of a proving ring. In this case pressure is applied on the bend of the U and the deflection of the extremities of the U is measured by means of a dial indicator. This device is readily calibrated and the only difficulty in its application is to be certain that the pressure is always applied at the same point of the U, so that there will be no change in the lever arm. Owing to the fact that in the making of the actual weld a number of the factors may bring about a change in pressure, it has been considered desirable to make pressure measurements dynamically during the making of actual welds. Both friction and inertia may cause a reduction in electrode pressure during the making of a weld if it becomes necessary for the electrode to follow through an appreciable distance in completing the weld. Inertia will, of course, retard the electrode system and frictional forces may change during the making of a weld, either in the direction of increasing or decreasing the pressure. A device for the dynamic measurement of pressure has been described in the literature.*

The electric pressure gage operates on the principle that fine resistance

* Hess, W. F., and Wyant, R. A., "A Method of Studying the Effects of Friction and Inertia in Resistance-Welding Machines," *The Welding Journal*, 19 (10), Research Suppl. 433-s to 440-s (1940).

wires subjected to compression will have their resistance decreased, and when subjected to tension will have their resistance increased. These fine resistance wires are cemented to the surface of a portion of the electrode holder and the windings are connected in a bridge circuit. The output of this bridge circuit is amplified so that it may be recorded by means of an electromagnetic oscillograph. Such a pressure gage may be used for static measurements as well as for dynamic measurements if desired. It is possible by means of properly conducted pressure measurements to evaluate a welding machine with regard to the amount of friction and inertia which is operative in the machine. Such measurements are often very informative as to the benefit of new designs of the mechanical system of welding machines.

Consistency Instruments for Resistance-Welding Machines

The characteristics of resistance-welding machines such as spot-, seam- and projection-welding machines are such that appreciable changes in electrode dimensions, electrode pressure and contact resistance of sheet and electrodes do not appreciably change the electrical input to the welding machine, yet these factors may change the quality or strength of the weld.

Where close shop supervision is directed at minimizing these variables, it has been proved that faulty welds from these variables can be practically if not entirely eliminated.

Since these factors are not appreciably reflected in the electrical behavior of the machine, electrical instruments or devices cannot be expected to accurately indicate changes in weld strength or weld quality because of these variables.

Other variables, however, beyond the control of the operator or maintenance crew, can be electrically indicated and among these are:

1. Voltage (fluctuations, variation or failure).
2. Current (variations caused by voltage changes, loose connections, high-resistance contacts, bouncing contacts, improper operation of tubes, variations caused by starting at different points on the voltage wave and the changes in the impedance of the secondary circuit whether it be because of changing the throat area, or by the introduction of magnetic metals into the throat of the machine).
3. Timing variations (because of the inaccuracies of non-synchronous control or faulty synchronous control operation or improper setting of the control).

It is possible to indicate all of these variations electrically because each of them will cause an appreciable change in I^2T input to the welding machine when all other variables remain constant. (I^2T equals the current squared multiplied by the time of current application.)

Ampere Second Consistency Indicator.—Probably the first instrument used to indicate spot-weld variations was a simple ammeter connected to the secondary of a current transformer, the current transformer being located in the primary circuit of the welding transformer. Each time a spot weld was made, the pointer would start up scale but before it reached a stable position, the current would cease to flow. Ballistically this instrument would swing up to some point on the scale and then return to zero. The deflection of this type of instrument for the conventional spot weld of, say,

1 to 15 cycles, is essentially proportional to IT. If the current should vary by as much as 10%, the deflection of the instrument would also vary by similar amounts. The deflection of the instrument for 4 cycles would be approximately 20% less than for 5 cycles. This type of indicator requires continuous observation by the operator.

Another device used in a similar manner gives a fairly accurate indication, namely, the recording ammeter. This instrument has the advantage of making a record but also requires constant observation by the operator if he is to catch any one weld which is likely to be faulty because of current or timing variations. Furthermore, a recorder of this type requires maintenance of the inking system and also the friction of the pen against the paper causes slight inaccuracies.

To give an audible signal when IT varies outside of certain limits, an ammeter was equipped with a photoelectric relay and light source arranged in such a manner that the pointer would interrupt the light beam when the

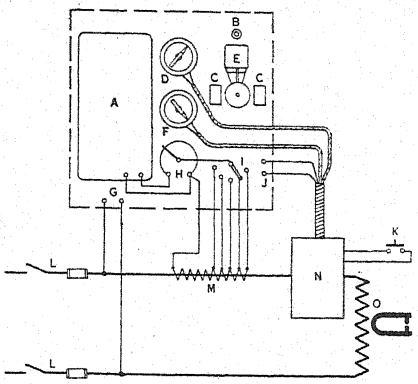


Fig. 47—Diagram of Connections of Weld Recorder to Welder Circuit, Current Transformer and Welder Control

deflection (or IT) was within certain limits. A gong would sound a single stroke when IT was within certain predetermined limits. If IT was greater than the allowable limits, the pointer would swing through the light beam causing one stroke and then upon the return would again interrupt the beam causing another stroke of the gong. If IT was insufficient, the gong would not strike at all. The operator, therefore, would know that the input to the welding machine was within the desirable limits if only a single stroke of the gong was heard each time a weld was made.

The foregoing devices require constant attention on the part of the operator to make them useful. Furthermore, the speed at which the equipments can operate is limited to approximately 20 or 25 welds per minute (in that the conventional ammeter and other similar instruments have a period of approximately one second).

Weld Recorder.—The weld recorder is a recording instrument, signaling device and lockout control that records on a paper chart the variations of

the electric input for each spot weld as compared with the input for other welds, and as compared with a predetermined normal. A connection diagram for this circuit is shown in Fig. 47.

It is so designed that when a variation of I^2T occurs which may be of sufficient magnitude to cause a poor weld (based on the predetermined settings of the recorder) a bell gives a continuous audible signal and the weld initiating circuit is automatically opened preventing subsequent welding until a push button is pressed. In addition the recorder chart indicates visually that the weld was not within the preset allowable limit for proper welding and shows whether the electric input was above or below normal.

The recording instrument is similar in appearance to a recording ammeter; however, the deflection is essentially proportional to I^2T. The moving element is mounted on jewel bearings and has no other mechanical restrictions to its movement; therefore, accuracy is assured (accuracy within 1%).

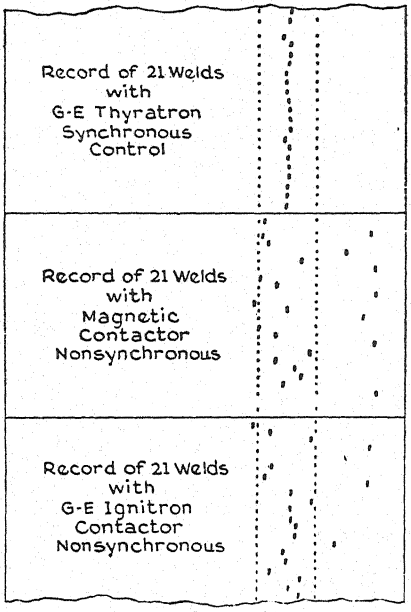


Fig. 48—Weld Recorder Record Charts

The instrument pointer is motored up scale when current flows. The speed is proportional to the square of the current. When the current flow ceases, the pointer immediately stops and a solenoid-operated bar strikes the pointer and makes a record in the form of a dot on the paper chart which passes over an inked ribbon. The maximum and minimum preset allowable limits of I^2T are also shown on the paper chart. After the record is made, the pointer is immediately motored back to the zero position to be ready for another weld. Welds can be recorded up to 100 per minute. Typical records from the weld recorder are illustrated in Fig. 48.

So that the weld recorder can be used over a wide range of timing and current, a tapped current transformer, a tap changing switch and a potentiometer are used to permit adjustment of the recorder within the allowable limits. The allowable limits are adjustable, but are usually set for plus or minus 15% I^2T.

A similar current transformer and potentiometer are also used with the ampere second consistency indicator.

Other Instruments or Devices for Use with Resistance Welding Machines.—A consistency indicating device similar to the ampere second consistency indicator has been used, but contains no movable elements. It is an electronic arrangement whereby the secondary output of the current transformer is rectified and applied to a capacitor. The ultimate capacitor voltage is in some relation to I^2T. Immediately after the weld current flow ceases, the voltage on the capacitor is compared with a standard voltage. If excessive voltage differences occur, an electrical signal is given which can be used for making an audible signal or electrically locking out of the welding machine operation.

Voltmeters, ammeters, oscillographs, oscilloscopes and cycle counters have all been used for various testing operations on welding machines or for laboratory work. They are not suitable, however, for regular production use except for occasional testing, indication or for trouble shooting.

Cycle Recorder.—A useful device for checking the duration of current flow is the cycle recorder. This is a small instrument with a frequency sensitive element in the form of a stylus which presses against a strip of paper which travels at several inches per second. Under this paper is a cylinder of graphite. The paper is driven through the instrument by a motor. When alternating current is applied to the recorder, the sensitive element vibrates in synchronism with the frequency. A mark is scribed on the paper such that it follows the alternating current and thereby permits one to count the number of half cycles that current is supplied to the welding machine for any one weld or series of welds.

Seam-Welding Indicators.—The weld recorder, consistency indicators, etc., can be used with seam-welding machines only for the purpose of showing the value of IT or I^2T for any one of several current impulses. There is required a suitable system of relays to close the circuit just before and open the circuit just after the one-power impulse which was selected as the one to be recorded. The weld recorder has been used for the purpose of recording one out of every ten or twenty impulses.

The cycle recorder can be continuously connected to a seam-welding machine for recording the cycles on and cycles off; however, this should be done only during short test runs to avoid excessive wear on the recorder. Moreover, counting of cycles for several minutes' run is a long tedious job.

CHAPTER 12

ELECTRODES, ELECTRODE HOLDERS AND CONDUCTORS FOR RESISTANCE-WELDING MACHINES*

General Application and Uses, Standards, Spot Welding Electrodes, Electrode Maintenance, etc., Seam Welding Wheels, Projection Welding Dies, Upset Butt and Flash Welding Dies, Electroforging Dies, Cross Wire Welding Dies, and Electrical Upsetting Dies.

General Applications and Uses

THE electrodes are one of the most essential parts of resistance-welding machines. Alloys were developed for the electrodes and other current-carrying members because copper had insufficient strength and annealed at too low a temperature. All of the alloys developed for electrodes, whether they be of the solid solution, precipitation hardening or refractory powder metal types, have higher annealing or softening temperatures (Fig. 1). At the same time their compressive strength together with resistance to abrasion or wear qualities have been greatly improved. While there has been some sacrifice in conductivity, the conductivity is amply high for the recommended uses (See Table 1 for properties of R. W. M. A. classes of alloys).

The physical and electrical requirements of the electrodes vary with the types of materials being welded. This is also true for the various types of welding employed, such as spot, seam, projection, butt, etc. The R.W.M.A. standards for alloys for electrodes and current carrying members of machines are as follows:

Group A—Copper Base Alloys.—Class 1: An all-purpose electrode material; a superior substitute for copper. Especially recommended for coated metals such as terneplate, galvanized stock, scaly stock, aluminum and aluminum alloys; used as spot-welding electrodes, seam-welder wheels, seam-welder shafts, etc.

Class 2: A superior electrode material for high-production work on clean carbon steel stock, some aluminum alloys, as well as yellow brass and the like. Used for spot-welding electrodes, seam-welder wheels, seam-welder shafts, etc.

* Prepared by a committee consisting of G. N. Sieger, S-M-S Corp., *Chairman;* J. A. Weiger, P. R. Mallory & Co., Inc.; C. L. Pfeiffer, Western Electric Co.; and O. M. Lundene, Chevrolet-Flint Div., General Motors Corp.

In the cast form, for high-strength castings with high conductivity such as gun welder arms and the like.

Class 3: Used for all projection, flash and butt-welding dies, spot and seam welding of stainless steel; also for current carrying bushings. In the cast form, where higher strength than in Class 2 is required.

Group B—Copper-Tungsten Alloys.—Class 10: Recommended for spot welding of stainless steel, yellow brass and the like, but excluding red brass and copper.

Class 11: Especially recommended for inserts and facings for flash welding dies, and light projection-welding, as well as seam-welder bushing inserts; facings for electroforging dies.

Class 12: Used for heavy projection-welding dies and electrical upsetting of rivets.

Class 13: Especially recommended for spot-welding tips and cross-wire welding dies for red brass, copper and the like.

NOTE: Above recommendations based on use with proper equipment.

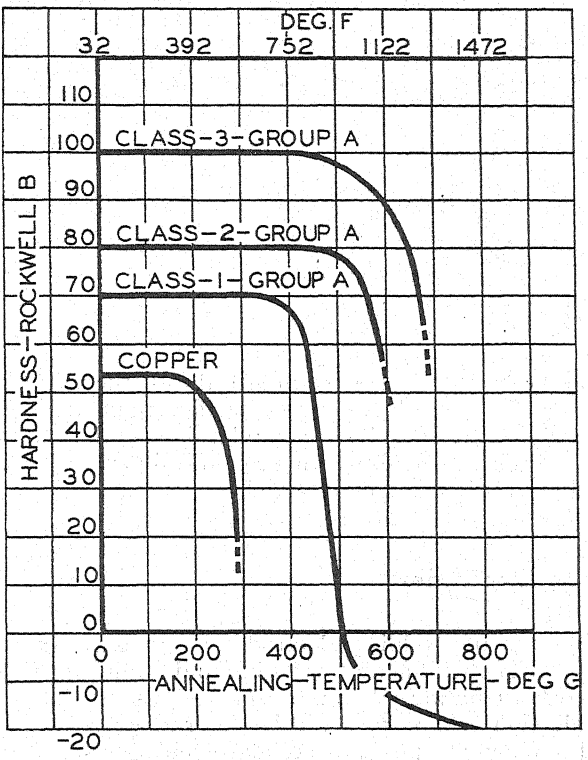


Fig. 1—Hardness and Annealing Temperatures of Copper Alloy Electrodes Compared to Copper

In reviewing the above classes, it will be noted that the requirements are for maximum conductivity with reasonable tensile strength, as in Class 1, through high conductivity with greater tensile strength, as shown in Class 3, to very high compressive strength with the desired lower conductivity, as shown in Class 13.

Table 1—Minimum Standard Requirements of R.W.M.A. Alloys

	Hardness Rockwell "B"		Conductivity, % of Copper		Ultimate Tensile Strength, Psi.		
	Cast*	Wrought	Cast*	Wrought	Cast*	Wrought	Availability
Group A							
Class 1	..	68†	..	80	....	60,000	Rods, Bars, Forgings
Class 2	55	75	70	75	45,000	65,000	Rods, Bars, Castings Forgings
Class 3	95	95‡	45	45	85,000	100,000	Rods, Bars Castings Forgings
					Ultimate Compressive Strength, Psi.		
Group B							
Class 10	..	78	..	40	....	135,000	Rods, Bars, Inserts
Class 11	..	98	..	30	....	160,000	Rods, Bars, Inserts
Class 12	..	100	..	29	....	185,000	Rods, Bars, Inserts
Class 13	..	38 Rockwell C	..	28	....	225,000	Rods, Bars, Inserts

* Based on cast tensile bars.
† For section not exceeding one inch square.
‡ 90 Rockwell "B" on finished rods.

In addition to the R.W.M.A. standard alloys, there are a number of other alloys available which for some specific applications have distinct advantages. However, the above compilation, if followed, will produce good, strong, consistent welds, with economical performance, if all other good operating conditions are maintained.

Spot Welding Electrodes

The design of a spot-welding electrode and material from which it is made will have a great influence on its life and quality of weld produced. There is almost an unlimited number of designs possible. The proper design and selection of materials will be determined by the type of work to be welded. Wherever possible, standard replaceable electrodes should be used in conjunction with a proper size water-cooled holder or electrode body. By this means the least possible electrode cost can be secured. Very economical electrodes are made with No. 1 or No. 2 Morse tapers. The R.W.M.A. Standard Morse Tapered electrodes are shown in Fig. 2.

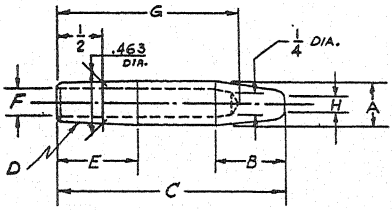
In some instances male or female threaded electrodes can be used to advantage.

Cooling.—Experience has shown that the life of spot-welding electrodes can be increased tremendously by proper water cooling. Efficient water

cooling will maintain a very high specific conductivity and keep the electrode material below the annealing point.

The water hole should be in correct proportion to the electrode diameter, otherwise the resultant cross-section of the electrode wall will be too small to carry the high current. A good rule to follow regarding the depth of the water hole is to make the distance from the end of the hole to the face of the electrode not greater than the diameter of the electrode.

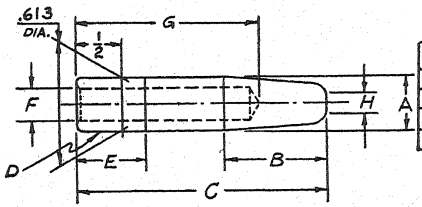
#1 MORSE TAPER—— POINTED.



A	B	C	MORSE TAPER D	E	F	G	H
.463	1/2	1	Nº1	1/2	9/32	5/8	1/8
.463	5/8	1 1/4	Nº1	1/2	9/32	3/4	1/8
.482	5/8	1 1/2	Nº1	7/8	9/32	1	1/8
.482	3/4	1 3/4	Nº1	7/8	9/32	1 1/4	3/16
.482	3/4	2	Nº1	7/8	9/32	1 1/2	3/16
.482	3/4	2 1/4	Nº1	7/8	9/32	1 3/4	3/16
.482	3/4	2 1/2	Nº1	7/8	9/32	2	3/16

Fig. 2(a)

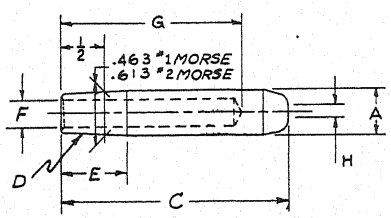
#2 MORSE TAPER —— POINTED.



A	B	C	MORSE TAPER D	E	F	G	H
.625	3/4	1 1/2	Nº2	3/4	3/8	3/4	1/4
.625	1 1/8	2	Nº2	3/4	3/8	1 1/4	1/4
.625	1 1/8	2 1/2	Nº2	3/4	3/8	1 3/4	1/4
.625	1 1/8	3	Nº2	3/4	3/8	2 1/4	1/4

Fig. 2(b)

#1 MORSE TAPER —— DOME
#2 MORSE TAPER

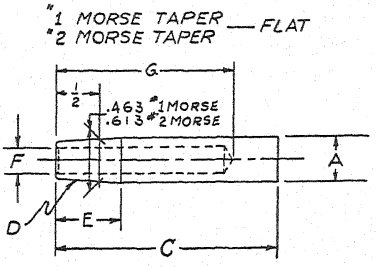


A	C	MORSE TAPER D	E	F	G	H
.463	1	Nº1	1/2	9/32	5/8	1/8
.463	1 1/4	Nº1	1/2	9/32	15/16	1/8
.482	1 1/2	Nº1	7/8	9/32	1 1/8	1/8
.482	1 3/4	Nº1	7/8	9/32	1 1/4	1/8
.482	2	Nº1	7/8	9/32	1 1/2	1/8
.482	2 1/4	Nº1	7/8	9/32	1 3/4	1/8
.482	2 1/2	Nº1	7/8	9/32	2	1/8

.625	1 1/2	Nº2	3/4	3/8	1	1/8
.625	2	Nº2	3/4	3/8	1 3/8	1/8
.625	2 1/2	Nº2	3/4	3/8	1 7/8	1/8
.625	3	Nº2	3/4	3/8	2 1/4	1/8

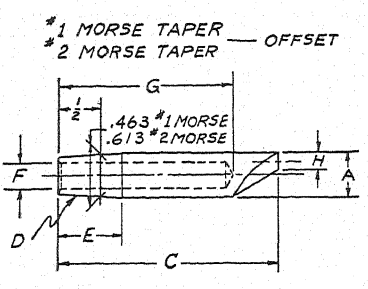
Fig. 2(c)

(*Fig. 2—Continued on next page*)



A	C	MORSE TAPER D	E	F	G
.463	1	Nº 1	1/2	9/32	5/8
.463	1 1/4	Nº 1	1/2	9/32	15/16
.482	1 1/2	Nº 1	7/8	9/32	1
.482	1 3/4	Nº 1	7/8	9/32	1 1/4
.482	2	Nº 1	7/8	9/32	1 1/2
.482	2 1/4	Nº 1	7/8	9/32	1 3/4
.482	2 1/2	Nº 1	7/8	9/32	2
.625	1 1/2	Nº 2	3/4	3/8	1
.625	2	Nº 2	3/4	3/8	1 3/8
.625	2 1/4	Nº 2	3/4	3/8	1 7/8
.625	3	Nº 2	3/4	3/8	2 1/4

Fig. 2(d)



A	C	MORSE TAPER D	E	F	G	H
.463	1	Nº 1	1/2	9/32	5/8	3/16
.463	1 1/4	Nº 1	1/2	9/32	3/4	3/16
.482	1 1/2	Nº 1	7/8	9/32	1	3/16
.482	1 3/4	Nº 1	7/8	9/32	1 1/4	3/16
.482	2	Nº 1	7/8	9/32	1 1/2	3/16
.482	2 1/4	Nº 1	7/8	9/32	1 3/4	3/16
.482	2 1/2	Nº 1	7/8	9/32	2	3/16
.625	1 1/2	Nº 2	3/4	3/8	1	3/16
.625	2	Nº 2	3/4	3/8	1 3/4	1/4
.625	2 1/2	Nº 2	3/4	3/8	1 3/4	1/4
.625	3	Nº 2	3/4	3/8	2 1/4	1/4

Fig. 2(e)

Fig. 2—R.W.M.A. Standard (Morse Tapered) Replaceable Resistance Welding Electrodes

It is very important to have the tube conducting the water into the electrode very close to the bottom of the hole in order to prevent steam pockets.

Electrodes for spot welding of stainless steel, yellow brass, red brass, copper and the like are made with a facing of copper-tungsten alloy (R.W.-M.A. Specification, Classes 10 or 13, Group B) brazed to a suitable backing, preferably of Class 1 or Class 2 materials. Several types of copper-tungsten faced electrodes are shown in Fig. 3.

R.W.M.A. recommended electrode materials for spot welding similar and dissimilar metals using conventional spot-welding methods are shown in Fig. 10. In addition to the recommended electrode materials, the chart gives information regarding the quality of the welds and special information pertaining to the various metals to be welded.

Electrode Holders.—The transfer of electric current and pressure from the spot-welder machine arms to the electrode is accomplished by means of holders. When used with replaceable Morse taper electrodes, it is essential that the seat provided be of very close tolerance dimensions so that there will be a minimum loss of energy between the holder and the electrode. The cross section of the holder must be adequate to carry the cur-

rent and to transmit the pressure. At the same time it must have provisions to assure effective circulation of water within the electrode.

Morse tapers make a very good electrical connection and water-tight seal. This is why they were selected. It is, however, essentially a gripping taper which means that the removal of the electrode is not readily

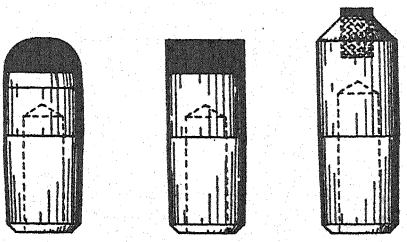


Fig. 3—Morse Taper Electrodes with Facings and Inserts of R.W.M.A. Electrode Materials, Group B, Classes 10, 11, 12, and 13

accomplished by the use of pliers without the possible deformation of the seat. In order to remove the taper electrodes without mutilating the seat in the holder provision should be made for an ejector feature in the holder itself, or for the use of some electrode ejecting tool. The use of pliers, wrenches, hammers, etc., is strongly discouraged in order not to mutilate the holder seat.

R.W.M.A. Standards for Straight and Offset Holders are shown in Fig. 4.

In addition to the R.W.M.A. Standard Holders which have solid bodies, holders with self-contained, adjustable spring pressures are advantageous where low inertia is desirable. Applications for low inertia water-cooled holders are as follows:

1. Spot and projection welding of light-gage (0.020 in. and under) non-ferrous metals having narrow plastic ranges, such as yellow brass, red brass, aluminum, etc.
2. Cross-wire welding of non-ferrous metals, such as for welding copper wire to a brass terminal.
3. For multiple spot or projection welding when used as an individually sprung holder.
4. For obtaining low pressures on large welding machines, the pressure systems of which do not reduce low enough.
5. For supplying a low inertia feature to welding machines having heavy and bulky moving members, thereby increasing the applications for which the machines might be used.

Electrode Maintenance.—The initial contour of the spot-welding electrode should constantly be maintained. Mushroomed electrodes should not be tolerated. Since mushrooming is the result of annealing, it follows that to keep the electrodes properly maintained they must be effectively cooled. The most damaging element to spot-welding electrodes is not pressure, but heat. The presence of water does not necessarily assure cooling. It must be circulating water to remove all steam pockets. Provision has been made in the recommended holders for adjustable cooling tubes so that circulation at the extreme depth of the electrode hole is assured. This is an important consideration too frequently minimized.

The shape and finish of the electrode face are of paramount importance. Finishes and shapes made by hand filing in the machine are not conducive to either good welds or long life. The frequent dressing of electrodes by machining in lathes or by the use of a dresser, as indicated in Fig. 5, or by a power-driven milling cutter, is strongly recommended.

The electrode seat of the holder should be maintained. Compounds must not be used to prevent water leaks between the electrodes and

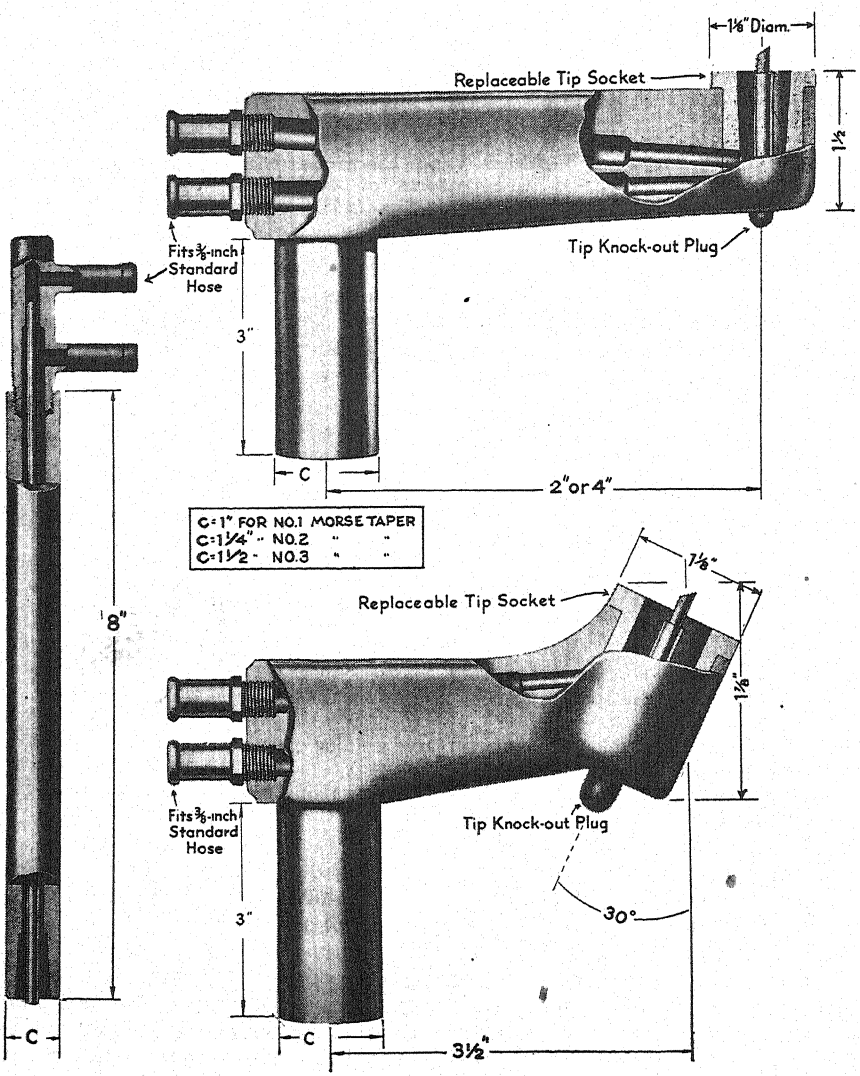


Fig. 4—R.W.M.A. Standards for Straight and Offset Holders

holders. The connection between the holder and the spot-welder arm should be free from dirt, oil or oxide, and should be firmly connected.

Seam-Welding Wheels

Lap Seam Welding.—Lap seam-welding wheels are used in the form of discs or rings, and the seam-welding electrode materials should be the same as used for welding the various metals as listed under "Spot-Welding Electrodes."

In many cases longer life can be obtained from the electrode wheel by using hardened idler or driving wheels attached to the welding heads. The use of these idler or driving wheels maintains the shape of the electrode wheels and thereby greatly reduces the number of dressings.

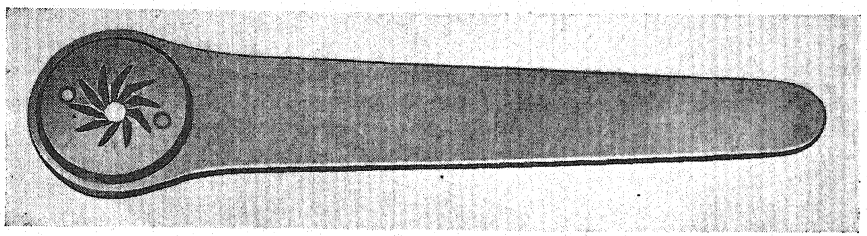


Fig. 5—Electrode Tip Dressing Tool

The R.W.M.A. standard sizes for lap seam-welding wheels are shown below:

7 in. O.D. x 3/8 in. thick
8 in. O.D. x 3/8 in. and 1/2 in. thick
10 in. O.D. x 3/8 in. and 3/4 in. thick

Butt Seam Welding.—For butt seam welding the electrode wheels are not in direct contact with the weld itself. For welding small diameter tubing and thin gage metal the same materials are recommended as mentioned under "Spot-Welding Electrodes." For welding heavy gage metal and large-diameter pipe best results can be obtained by the use of electrode wheels with the proper hardness and conductivity, depending upon the type of machine used, the wall thickness and the grade of material being welded.

Cooling.—Water cooling is just as important for seam-welding wheels as it is for spot-welding electrodes. Seam-welding wheels which are hollow to allow for inside water cooling are not only expensive but sometimes impractical. Simpler designs of wheels can be worked out which are flood cooled, that is, by spraying water directly on the work and wheels at the point where the weld is being made. Even better results are obtained by submerging the work being welded under water.

Projection-Welding Dies

For projection welding it is necessary to maintain a parallel relation be-

tween the opposing faces of the dies. If the dies wear non-uniformly, or if the projections produce cavities, non-uniform pressures and current densities will result, thereby producing non-uniform welds and a large number of unwelded sections.

Projection-welding dies have flat surfaces which contact much larger areas than do spot-welding electrodes. The deterioration of the dies is not so great as in the case of spot welding, since the heat and wear are distributed over larger areas.

Electrode die materials which are most suitable for projection welding are those which have the greatest hardness and the proper electrical con-

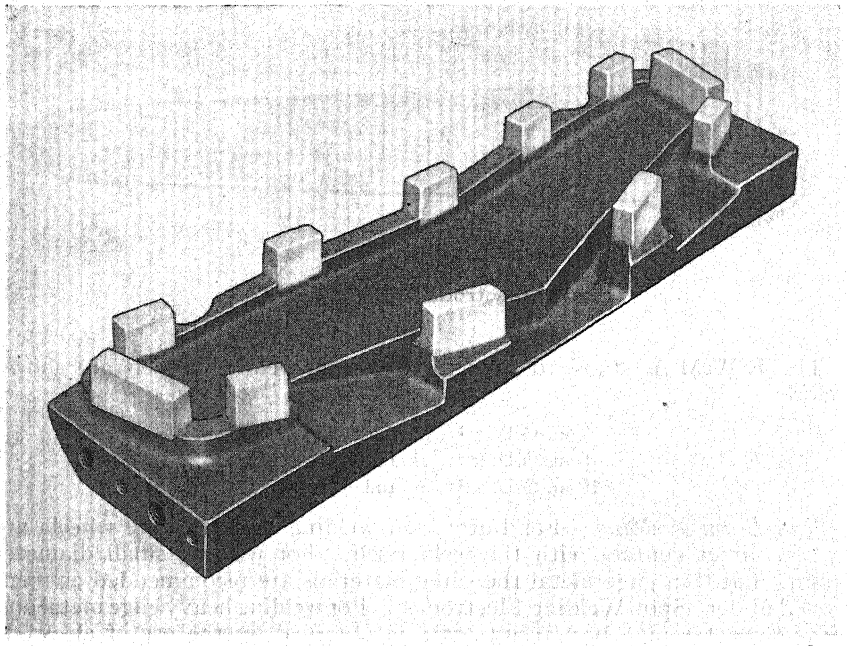


Fig. 6—Dies for Projection Welding—Inserts in Lighter Tone Are Copper-Tungsten Alloy, Silver Brazed to Hardened Copper Alloy Backing

ductivity. It has been found that best results can be obtained with die materials having a minimum hardness of 90 Rockwell "B" and with an electrical conductivity not less than 30% that of copper (R.W.M.A. Specification, Classes 11 and 12, Group B). These alloys are used as facings for plugs which are fitted into the water-cooled backing. If the projections are close together, an entire facing of the alloy approximately $^1/_4$ in. thick is recommended. The facing material can be readily silver brazed to a suitable copper or copper-base alloy, water-cooled backing. Where the pressures are extremely high a copper alloy which can be heat treated directly

after brazing is recommended in order to produce the necessary compressive strength in the backing material.

Figure 6 shows a projection-welding die made by silver brazing pieces of the above hard copper alloy to a copper alloy base which is hardened by heat treatment after silver brazing.

Figure 7 shows a projection-welding die made by force fitting hard copper alloy-faced plugs into the water-cooled copper alloy die-backing. When using replaceable plugs it is necessary to have a small knock-out hole under each plug to facilitate replacement. For certain types of dies using replaceable plugs, it is desirable to use adjusting screws under the plugs for the initial set-up and subsequent wear.

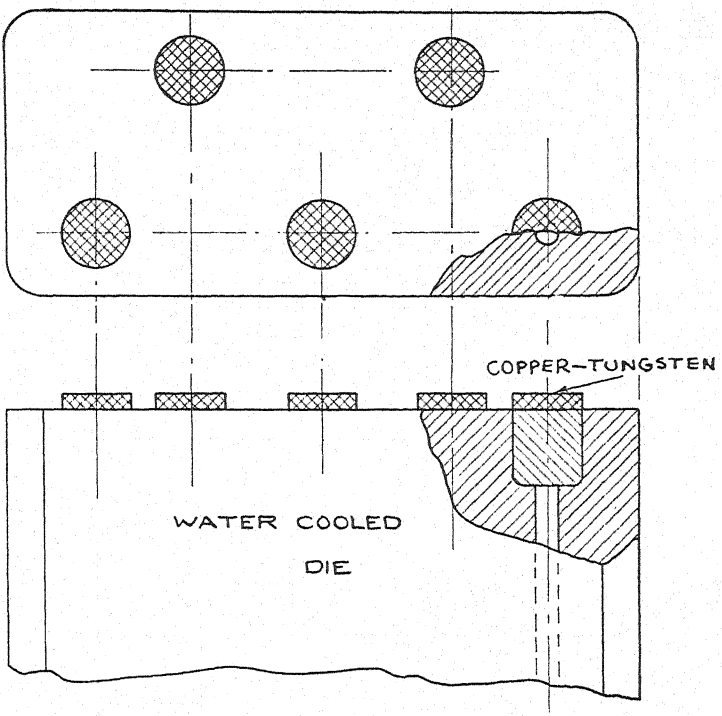


Fig. 7—Projection-Welding Dies Made by Force Fitting Hard-Copper Alloy-Faced Plugs Into Water-Cooled Copper Alloy Die-Backing

For certain projection-welding jobs good results are obtained by using dies made entirely from a hard copper alloy (R.W.M.A. Specification, Class 3, Group A).

When projection-welding dies are put in a machine for the first weld, care must be exercised in the machine setting. An incorrect machine adjustment may injure or ruin the dies during the first weld. For some applications, a coat of cup grease applied to both dies when new seems

to help, as it is noted that after the faces have become slightly oxidized the tendency for the work to stick to them is minimized.

Butt- and Flash-Welding Dies

Butt- and flash-welding die electrodes must be constructed of the proper materials to overcome the following difficulties:

1. Mushrooming, which causes non-uniform heating and telescoping, results in a high percentage of rejected parts.

2. The flashing produced during the welding operation must not adhere to the surface of the die. If the flash does adhere to the surface of the die, frequent cleaning and filing are necessary which slows up production. In some instances, air-operated scrapers are used on straight flash-welding dies, or an air jet, actuated in conjunction with the clamp release, automatically cleans the dies of the more or less loose particles. By keeping the dies clean the life is increased. In some cases, if such a flash gets on the face of the die it will fuse into the metal, making it necessary to redress the entire die.

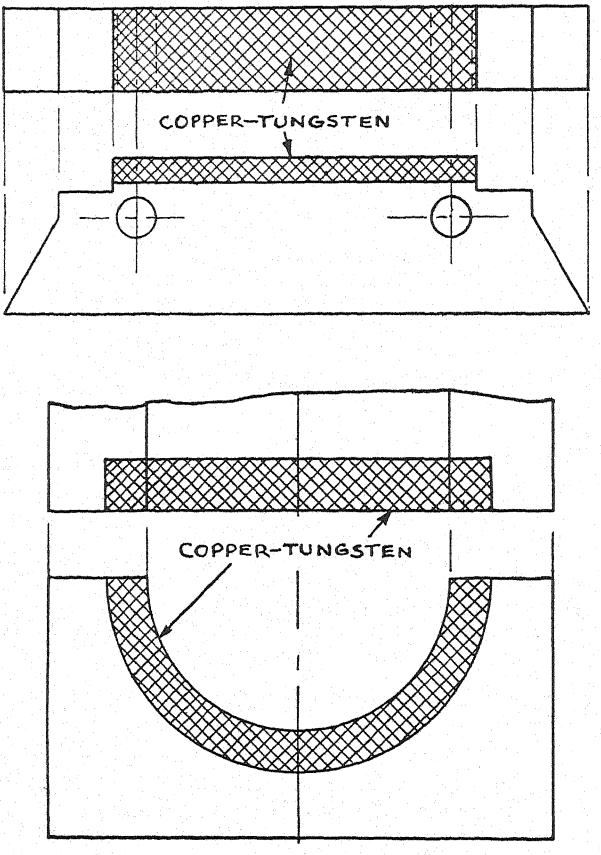


Fig. 8—Flash Welding Dies Faced with Copper-Tungsten (R.W.M.A. Class 11, Group B Alloy)

For making short flash welds, for flash welding very heavy materials, for flash welding tubes and metals of large cross-section end to end, most satisfactory results can be obtained by facing water-cooled dies with a suitable grade of hard copper alloy. Best results can be obtained with copper alloy facings which have a minimum hardness of 90 Rockwell "B" and with an electrical conductivity not less than 30% that of copper (R.W.M.A. Specification, Class 11, Group B). For certain special applications, where the current density is extremely high or where the machine is being operated at its peak or over-load capacity, it is important that the facing material have the proper electrical conductivity. The hard copper alloy die-facing materials can be readily silver brazed to the water-cooled backing. After brazing, certain types of alloys must be heat treated to obtain the desired hardness and conductivity.

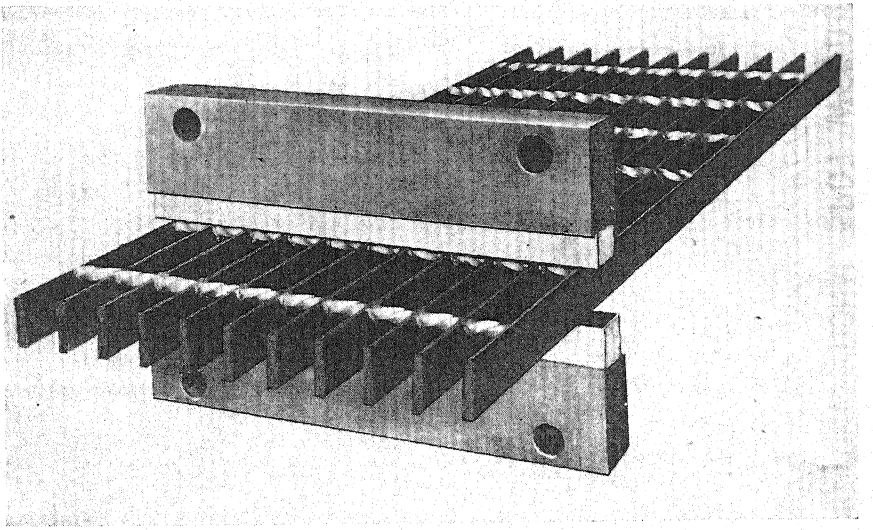


Fig. 9—Typical Installation of Electroforging Dies, Lighter Portion of Dies Are Faced with Copper-Tungsten (R.W.M.A. Class 11, Group B)

Figure 8 illustrates different types of hard copper alloy-faced dies used for flash welding. Flash-welding dies for certain small and medium sections, of a complicated outline, can be made most economically by casting or forming the entire die from the proper alloy to the desired size and shape. This eliminates a great deal of expensive machine work.

Electroforging Dies

The die material for this process is an important factor in its success because a material is required with a high hardness, high-compressive strength and high-electrical conductivity and one which must not anneal when subjected to rather high temperatures. The best electrode material for electroforging dies is copper-tungsten (R.W.M.A. Specification.

R.W.M.A. RECOMMENDED ELECTRODE MATERIALS FOR SPOT WELDING SIMILAR AND DISSIMILAR METALS USING CONVENTIONAL SPOT WELDING METHODS

TO WELD SIMILAR METALS

FERROUS

TO WELD SIMILAR METALS READ BLOCK UNDER METAL TO BE WELDED	TIN PLATE STEEL		TERNE PLATE STEEL		GAL-VANIZED IRON ZINC PLATE		CADMIUM PLATE STEEL		CHROME PLATE STEEL		STAIN-LESS STEEL 18-8 TYPE		SCALY H.R. STEEL		C.R. STEEL H.R. STEEL CLEAN	
	B	I	A	I	A	I (5)	B	I	A	II	A	III (8)	B	I (11)	A	II
	I	3	I	3	I (5)	3	I	3	II	3	III (8)		I (8)	2	II	

NON-FERROUS

ALUM-INUM	ALUM-INUM ALLOYS DURA-LUMINUM	CUPRO NICKEL	NICKEL SILVER	NICKEL	NICKEL ALLOYS MONEL NICHOME (HIGH RES)	BRASS YELLOW 25%-40% ZINC	PHOSPHOR BRONZE GRADE A, C & D	SILICON BRONZE EVERDUR OLYMPIC DURONZE HERCULOY
B	I (8)	B	I (8)	A	II	B	II	A	II	A	II	A	II	A	II	A	II
I (8)	2	I (8)	2	II		II		II		II		II		II		II	

TO WELD DISSIMILAR METALS

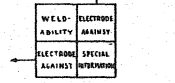
FERROUS ALLOYS	STAIN-LESS STEEL 18-8 TYPE		CHROME PLATE STEEL		CADMIUM PLATE STEEL		GAL-VANIZED IRON		TERNE PLATE STEEL		TIN PLATE STEEL	
COLD ROLLED STEEL HOT ROLLED STEEL, CLEAN	A	II (8)	A	II	B	II	B	I	A	I (11)	B	I
	II		II	3	II	3	II	3	II	3	II	3
TIN PLATE STEEL			B	II	B	I (11)	B	I	B	I (11)		
			I	3	I	3	I	3	I	3		
TERNE PLATE STEEL	B	II	B	II	B	I (8)	B	I				
	I	3	I	3	I	3	I	3				
GALVANIZED IRON ZINC PLATE	B	II	B	II	B	I						
	I	3	I	3	1	3						
CADMIUM PLATE STEEL	B	II	B	II								
	I	3	I	3								
CHROME PLATE STEEL	A	III (11)										
	II	3										

NON-FERROUS ALLOYS	NICKEL ALLOYS		NICKEL		PHOSPHOR BRONZE		SILICON BRONZE		YELLOW BRASS		NICKEL SILVER	
CUPRO NICKEL	B	II			B	II	B	II			B	II
	II				II		II				II	
SILICON BRONZE EVERDUR-OLYMPIC DURONZE-HERCULOY					B	II	A	II	B	II		
					II		II		II			
NICKEL SILVER	B	II			B	II	B	II				
	II	I			II	I	II					
NICKEL ALLOYS	A	II	A	II								
	II		II									
STAINLESS STEEL 18-8 - TYPE	B	II	B	II								
	III (5)	1	II (11)									

ALUM-INUM	
ALUMINUM ALLOYS DURALUMINUM	B I (8)
	I (11) 2

LEGEND

BLOCK INTERPRETATION



WELDABILITY

A EXCELLENT
B GOOD

ELECTRODES
R.W.M.A. SPECIFICATIONS

I - GROUP A CLASS 1
II - GROUP A CLASS 2
III - GROUP A CLASS 3

NOTE: ELECTRODE MATERIALS IN CIRCLES ARE SECOND CHOICE - EXAMPLE (8)

SPECIAL INFORMATION

1 - SPECIAL CONDITIONS REQUIRED
2 - GOOD PRACTICE RECOMMENDS CLEANING BEFORE WELDING
3 - IF PLATING IS HEAVY, WELD STRENGTH IS QUESTIONABLE

These recommendations for electrodes can be effective only when the other essential factors of the correct time, current and pressure are properly controlled.

This chart adopted by the Resistance Welder Manufacturers Association embodies the best general recommendations that can be made for the selection of the proper electrode materials for spot welding similar and dissimilar metals.

Fig. 10—R.W.M.A. Recommended Electrode Materials for Spot Welding Similar and Dissimilar Metals Using Conventional Spot-Welding Methods

Class 11, Group B), silver brazed to a suitable base metal backing. Figure 9 illustrates a typical installation of the above mentioned dies used for producing electroforged grating.

Cross-Wire Welding Dies

For cross-wire welding, the same classes of electrode materials are recommended as mentioned under "Spot-Welding Electrodes." In order to obtain maximum life from the electrodes, grooves should be machined in the dies to properly fit the wires being welded, wherever possible.

Electrical Upsetting Dies

The principal problem in electrical upsetting is the selection of the proper die materials. This operation requires dies that combine the following qualities:

1. High strength in compression.
2. High hardness at elevated temperatures.
3. Low thermal conductivity.
4. Resistance to oxidation at elevated temperatures.
5. Resistance to sticking to work being upset.

The best die material for this application is a tungsten-copper alloy facing (R.W.M.A. Specification, Class 12, Group B), silver brazed to a suitable water-cooled backing. The Rockwell hardness of the facing should be a minimum of 100 Rockwell "B", and the electrical conductivity should be approximately 25% that of copper. It is very important that the conductivity be fairly low, otherwise the end of the metal being upset will be chilled too rapidly and not upset uniformly.

CHAPTER 13

THERMIT WELDING*

Nature of Thermit and the Thermit Reaction, Applications, Methods of Welding, Description of Materials and Equipment and of Methods of Making Welds, Quantity of Thermit Required, Crankshaft Repairs, Steel Mill Repairs, Rail Welding on Street Railways, Rail Welding on Steam Railroads, Rail Welding in Coal Mines, Making Special Track Work, Locomotive Repairs, Cast-Iron Repairs, Marine Repairs.

THE entire science of aluminothermics is based on a discovery made by a prominent scientist more than forty years ago. The aluminum reduction of ores and oxides had been practiced prior to then, but the usual procedure had been the same as that employed in carbon or silicon reductions. The entire mass, oxide and reducing agent, was placed in a conducting-wall crucible and heated from the outside until reaction took place. Because aluminum, however, has so much greater affinity for oxygen than the other elements used for reducing purposes, the reactions obtained when this method was followed were so violent as to be explosive. The discovery referred to above was that, when aluminum was used as a reducing agent, the reaction could be initiated internally and in a cold mixture, and would, in from 20 to 30 seconds, convert any quantity of the mixture in the crucible into a seething mass of molten metal and supernatant slag.

This discovery, made in 1895, or 1896, in an attempt to reduce chromium and manganese, led to a patent application covering the process, and the initial patent was granted on March 16, 1897.

Although it was realized that extremely high temperatures were created by the reaction, it was not until a year or so later that the first attempts were made to utilize these temperatures as a source of heat for welding. Following the original experiments in welding, however, development was rapid and a process was evolved for the use of the reaction in welding on a commercial scale. Known as the Thermit welding process, this method was introduced in America by the Goldschmidt Thermit Company, organized in 1902. In 1918, the company was acquired by and became part of the Metal & Thermit Corporation.

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* Prepared by a committee consisting of J. B. Tinnon, Metal & Thermit Corp., *Chairman;* E. M. T. Ryder, Third Avenue Railway System.

NATURE OF THERMIT AND THE THERMIT REACTION

Thermit, as employed for welding, is a mechanical mixture of finely divided aluminum and of iron oxide in the form of magnetic iron scale. The proportions are, roughly, three pounds of iron scale to one of aluminum. This mixture reacts according to the chemical formula

$$8Al + 3Fe_3O_4 = 9Fe + 4Al_2O_3$$

Thus, expressed in weights, approximately eight parts aluminum plus three parts iron oxide will produce, when reacted, nine parts steel and four parts alumina slag.

The temperature resulting from the reaction is computed as being more than 5000°F. Due to the chilling effect of the crucible, however, the temperature of the liquid steel as poured into the mold for welding is slightly lower and has been measured at approximately 4500°F., which shows Thermit steel to be about twice as hot as ordinary molten steel.

The reaction is non-explosive and relatively slow, requiring about 30 seconds. No danger is incurred in handling or storing the mixture as an initial temperature of 2000 to 2100°F. is needed for ignition. To start the reaction then, a special ignition powder, composed largely of barium peroxide, is employed. This ignition powder is not dangerous to use or to store as it is designed to be ignited by the flare of a match and cannot be lit by the burning wood. In use, however, the container in which it is packed must be kept tightly closed in order to prevent sparks from the Thermit reaction dropping into the powder. It is also important that the Thermit mixture be kept dry as, once allowed to become wet or damp, it cannot be restored to its original state.

Actual Thermit mixtures used for welding contain other materials than aluminum and iron oxide. In designing such mixtures many variables, controlling both the time and the temperature of the reaction, as well as the chemical analyses of the resultant weld metals, are taken into account. For example, through the addition of metallic elements, either by means of metallic pieces, which are melted during the reaction, or in the form of combinations of oxides of elements with aluminum, a wide variation in the analysis of Thermit steel is provided. Table 1 gives the chemical formulas of the aluminum reductions of a number of oxides. By the same means the tensile strength, ductility and hardness of the resultant steel are also controlled, and the range of physical properties made possible includes tensile strengths from 50,000 psi. up to 110,000 psi., with corresponding ductilities of over 40% in 2 in. down to zero.

The average analysis of Thermit steel employed for welding is

Carbon	0.25 to 0.35
Manganese	0.40 to 0.60
Silicon	0.09 to 0.20
Sulphur	0.03 to 0.04
Phosphorus	0.04 to 0.05
Aluminum	0.07 to 0.18

A Thermit weld of this composition has an average tensile strength of about 72,000 psi. with an elastic limit of about 36,000; in fact, although

Table 1—Formulas Showing the Aluminum Reduction of Various Oxides

Metallic Oxides		Aluminum		Resultant Slag		Resultant Metal
$3Fe_3O_4$	+	8Al	=	$4Al_2O_3$	+	9Fe
Fe_2O_3	+	2Al	=	Al_2O_3	+	2Fe
$3Mn_3O_4$	+	8Al	=	$4Al_2O_3$	+	9Mn
Cr_2O_3	+	2Al	=	Al_2O_3	+	2Cr
WO_3	+	2Al	=	Al_2O_3	+	W
$3V_2O_5$	+	10Al	=	$5Al_2O_3$	+	6V
$3TiO_2$	+	4Al	=	$2Al_2O_3$	+	3Ti
3NiO	+	2Al	=	Al_2O_3	+	3Ni
MoO_3	+	2Al	=	Al_2O_3	+	Mo
$3SiO_2$	+	4Al	=	$2Al_2O_3$	+	3Si
B_2O_3	+	2Al	=	Al_2O_3	+	2B
$3Co_3O_4$	+	8Al	=	$4Al_2O_3$	+	9Co

cast, Thermit weld metal may be regarded as actually having physical properties closely approaching those of forged steel.

It is because Thermit steels are produced through the reduction of extremely pure iron oxide by an almost perfectly pure aluminum that they possess these physical properties without refinement by working. Ordinary cast steels are refined from pig iron and other impure materials. On solidifying, the impurities tend to gather along grain boundaries so that fractures in cast steel always occur along the grain boundaries within areas of impurity. The purity of the Thermit ingredients, however, eliminates most of this grain boundary condition and fractures in Thermit steel occur almost without exception through the grains. Thermit welds, therefore, although cast, have all the properties of forged steel.

The most commonly used Thermits for welding ferrous metals are:

Plain Thermit—a mixture of finely divided aluminum and iron oxide, which is the basis for all thermit mixtures.

Forging Thermit—which is plain Thermit with the addition of nickel, manganese and mild steel punchings, and is used in welding steel.

Cast Iron Thermit—consisting of plain Thermit with additions of ferrosilicon and mild steel punchings, used for welding cast iron.

Wabbler Thermit—designed to produce a hard, wear-resistant machinable steel for building up worn wabbler ends of rolls and pinions in steel mills.

APPLICATIONS

The process is employed throughout industry for the welding of heavy sections of ferrous metals. Until recently its use has been limited to the repair of housings, frames, shafts and other parts of heavy machinery and equipment, including stern frames of ships, and to rail welding on street railways and steam railroads, in coal mines and on the runways of heavy cranes. In addition, it has been employed extensively by steel mills for the reclamation and emergency repair of broken rolls, pinions and similar parts, as well as for the replacement of metal worn away in service on such parts as wabblers of rolls and pinions. Of late, however, there has been a tendency to fabricate heavy parts by means of Thermit welding.

By incorporating into the design of heavy units simple forgings, small

castings or flame-cut shapes Thermit welded together, the cost of heavy pieces can often be reduced to a fraction of what it would be if large intricate castings were employed. In addition, the difficulties of obtaining sound metal where very large castings must be poured are eliminated. At the same time, many of the inherent delays of cast construction can be avoided and production can be effectively speeded. This is particularly true where changes in design are involved or entirely new units are to be built, since welded fabrication eliminates the costly, time-consuming work of making new patterns.

While many of these same advantages apply to welded fabrications involving other welding processes, where very heavy sections are involved the Thermit process may be the only practical method. In the first place, preparation of parts for Thermit welding is simpler than that required with other welding methods and usually may be accomplished by flame cutting, eliminating the need for machining of intricate joint designs, always a slow, expensive operation. Also, time required for Thermit welding, including the construction of molds and preheating, is invariably much less than that needed to deposit weld metal layer by layer, in thin layers, as must be done, for example, in electric welding. In addition, a properly made Thermit weld has no locked-in, internal stresses and, therefore, stress relieving, which would be mandatory in a heavy, arc-welded structure, but which might be out of the question because of size, is unnecessary when Thermit welding is employed.

Further, with electric welding, positioning of heavy welds is frequently required to permit the use of high quality, down-hand welding rods and thus to assure weld soundness and proper physical properties. Very large structures, however, may be difficult to handle because of size and shape. With Thermit welding, no manipulation of the unit during welding is required.

Typical parts constructed by the process include a blooming mill pinion housing, made of 8-in. plate, a group of heavy H-beams built to form the body of a 250-ton capacity freight car and a number of fabricated stern frames for Class C-1, C-2 and C-3 cargo ships built for the U. S. Maritime Commission, in addition to much Navy work.

METHODS OF WELDING

Thermit welding includes two distinct methods or classifications. In the first, or pressure method, only the heat of the slag and the heat of the metal resulting from the reaction are utilized. In the second, or fusion method, which is more widely employed, the Thermit steel is deposited as weld metal.

Among the applications of the pressure method of Thermit welding is the welding of pipe. Special clamps are attached to the pipe and a mold applied. The accompanying diagram (Fig. 1) shows the way in which the slag and the superheated steel are used to bring the pipe to welding temperature. Following this operation, the clamps are drawn up to force the ends of the pipe together and to provide a pressure butt weld.

While this method of welding pipe has a number of advantages, such as

great strength, with little, if any, alteration of the inside diameter of the pipe, in pipe sizes over 2 in. O.D., it is more costly than electric arc or acetylene welding and its use consequently has been limited. It is employed, however, by manufacturers of superheaters and similar equipment, where pipe in large units, shop-built in sections, must be welded together when the sections are joined during installation. This method is sanctioned by the A.S.M.E. Boiler Code for such work as well as for the safe ending of boiler tubes.

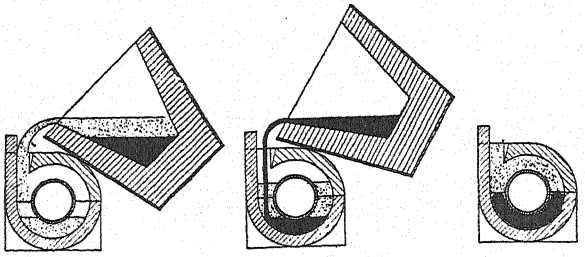


Fig. 1—Thermit Pipe Welding Operation

A. Slag flowing into mold and coating outside of pipe and inside of mold.

B. Slag in mold and steel following, displacing slag in bottom part.

C. Both slag and steel in mold but steel separated from pipe and mold by film of slag.

The more widely used fusion method of Thermit welding is employed throughout industry for welding heavy sections of ferrous metals.

In making a weld by this method, the first step is the lining up of the parts and the cutting of a parallel-sided gap at a point where the weld is to be made, the width of the gap depending on the size of the section. Around the break or joint, a wax* pattern is formed and a refractory sand mold is built, which provides an annular space at the weld. The part is then preheated by means of kerosene and air blown into the mold through an opening. Preheating, which continues until the parts reach red heat is depended on to burn out the wax of the pattern and to dry out the mold. Reaction is started by means of a small quantity of ignition powder placed on top of the Thermit in the crucible and when the reaction is completed the crucible is tapped, allowing the Thermit steel to run into the mold. This steel, having 100% superheat and being held in place between and around the ends of the parts to be welded, gives up its superheat to these parts, fusing and solidifying with them upon cooling.

DESCRIPTION OF MATERIALS AND EQUIPMENT AND OF METHODS OF MAKING WELDS

Most Thermit welds, whether repairs to crankshafts, stern frames of ships or heavy steel mill rolls, are made in more or less the same general

* Yellow pattern wax available from supplier of Thermit.

way. The following description, therefore, is for the purpose of covering a typical welding operation and only the special features peculiar to particular types of work will be covered further on under their respective headings.

Crucibles.—The Thermit reaction takes place in a magnesia-tar lined crucible (Fig. 2), which has at the bottom a hard-burned magnesia stone,

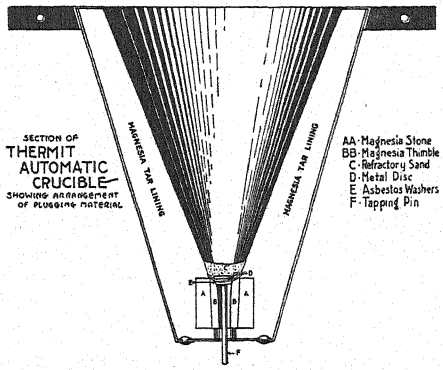


Fig. 2

AA. Into this stone, a smaller magnesia stone or thimble, *BB*, is fitted, providing a channel, through which the Thermit steel may run. This thimble is removed by gently knocking it upward and a new thimble is used for each reaction. The crucible is closed before being filled with Thermit by inserting the thimble, *BB*, wrapped with one thickness of uncreased paper. The thimble is then plugged by suspending the tapping pin, *F*, through the thimble and placing over it the asbestos washers, *E*, and the metal disc, *D*. The disc, *D*, is covered with refractory sand, *C*, the entire contents of the package furnished being used in each crucible.

Charging the Crucible.—Charging the crucible consists simply of placing in it the correct quantity of Thermit. Before charging, however, it is important to mix the Thermit thoroughly. Then a small quantity is placed gently on top of the plugging material before pouring the remainder into the crucible.

Tapping the Crucible.—The crucible is tapped by knocking the tapping pin sharply upward into the crucible with a tapping spade or flat piece of iron approximately $1\frac{1}{2}$ in. x $\frac{1}{4}$ in. x 4 ft. long.

After crucibles have been used for several reactions, they may wear at the bottom and additional care must then be used in plugging to avoid self-tapping. Worn crucibles can be patched with magnesia tar to prolong their life. When linings are so far gone as to preclude further use, crucibles may be completely relined.

Preheater.—The regular Thermit preheater (Fig. 3) operates with compressed air and either gasoline or kerosene. It is fitted with one or two burners, as desired, and with needle valves to give close regulation of the mixture of air and fuel so that good combustion may be obtained at all times.

For general work the double burner preheater is more satisfactory as it permits the use of one burner for preheating and the other for expanding. This is essential where one member of a double bar frame is being welded, for while the parts to be welded are being preheated the opposite member can be heated with the second burner and expanded to avoid shrinkage strains when the weld cools. In large welds the two burners are required and operate through two heating gates.

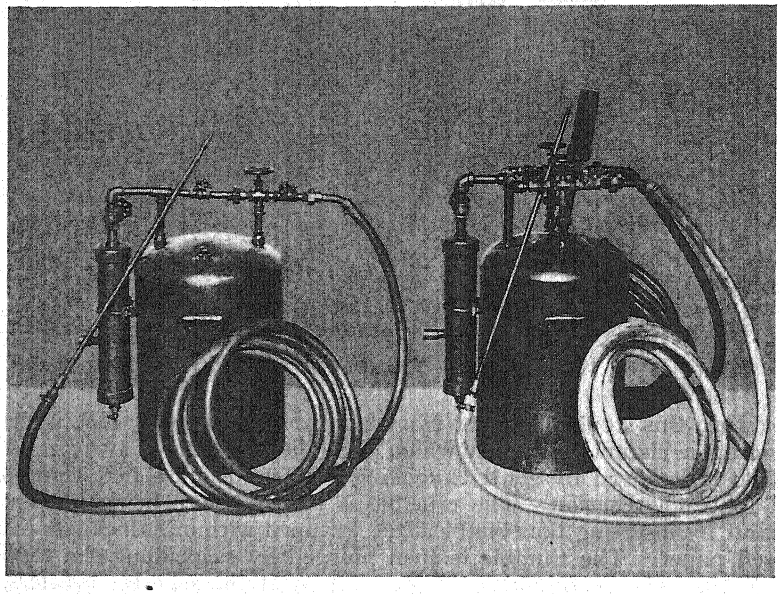


Fig. 3—Single-Burner and Double-Burner Preheater, Showing Water Separators and Flaming Burner Attachment. These Preheaters Operate on Either Gasoline or Kerosene, Although the Latter Is Recommended

The crucible and preheater comprise the only permanent pieces of apparatus required for Thermit welding in general repair work. Details of various size crucibles are given in Table 3.

Molding Material.—It is highly important that proper molding material be used in Thermit welding. The use of impure materials may result in blow-holes or glass-like inclusions in the weld metal. Material with poor binding qualities may cause breaking down of parts of the mold and result in burned parent metal or lack of fusion between parent metal and weld metal.

Making the Weld

Cutting Out Fracture.—To gage the allowance to be made for contraction of the weld, as explained later on, it is desirable, before lining up the parts, in preparation for cutting the gap to place tram marks on the parts to be welded. These marks are made at points outside of the areas to be covered

by the mold box. The metal may then be cut out along the line of fracture with an oxyacetylene torch so that a straight-sided gap of from $^3/_8$ in. to $2^3/_4$ in. is provided. The amount of opening depends on the size of the section to be welded and is shown in Table 2.

Table 2—Recommended Thermit Weld Dimensions and Portions

Section Width Height Inches	Gap Inches	Collar Inches	Riser Dia. Inches	No. Pouring Gates Dia. Inches	No. of Heating and Connecting Gates and Dia. Inches	Thermit Required Pounds	Section Width Height Inches
2x 2	3/8	1⅝x ⅜	¾	1—1	1—1	7	2x 2
2x 4	½	1¾x ½	¾	1—1	1—1	10	2x 4
3x 3	½	1⅞x ½	1	1—1	1—1	11	3x 3
3x 6	⅝	2⅛x ⅝	1	1—1	1-1¼C & 1-¾C	22	3x 6
4x 4	⅝	2⅛x ⅝	1	1—1	1—1¼	16	4x 4
4x 8	¾	3¼x ¾	1	1—1	1-1¼C & 1-¾C	42	4x 8
5x 5	¾	3 x ¾	1⅛	1—1	1—1¼	32	5x 5
5x 8	⅞	3⅛x ⅞	1½	1—1	1-1¼C & 1-1C	50	5x 8
6x 6	⅞	3⅛x ⅞	1½	1—1	1—1¼	44	6x 6
6x 9	⅞	4 x ⅞	1½	1—1	2—1¼C	70	6x 9
7x 7	⅞	3⅞x ⅞	2	1—1	1—1¼	65	7x 7
7x10	1	4½x1	2	1—1	2—1¼C	100	7x10
8x 8	1	4⅛x1	2	1—1	1—1¼	85	8x 8
8x12	1⅛	5⅛x1⅛	2	1—1	2—1¼C	145	8x12
9x 9	1⅛	4⅞x1⅛	2	1—1¼	1—1¼	115	9x 9
9x13	1¼	5⅝x1¼	2½	1—1⅛	2—1¼C	200	9x13
10x10	1⅛	5¼x1⅛	2½	1—1¼	1—1¼	150	10x10
10x15	1⅛	6⅝x1⅛	2½	1—1¼	2—1¼C	260	10x15
11x11	1¼	5⅝x1¼	2½	1—1⅛	2—1¼C	200	11x11
11x16	1⅛	6⅜x1⅛	2½	1—1¼	2-1¼C & 1-1¼NC	315	11x16
12x12	1⅛	6¼x1⅛	2½	1—1¼	2—1¼C	240	12x12
12x18	1½	7⅜x1½	3	1—1½	2-1¼C & 1-1¼NC	415	12x18
13x13	1⅜	6⅝x1⅜	2½	1—1¼	2—1¼C	300	13x13
13x19	1⅛	7⅞x1⅛	3	1—1½	2-1¼C & 1-1¼NC	475	13x19
14x14	1⅛	7⅛x1⅛	3	1—1½	2—1½C	360	14x14
14x20	1⅝	8¼x1⅝	3	1—1½	2-1½C & 1-1½NC	600	14x20
15x15	1½	7½x1½	3	1—1½	2—1½C	415	15x15
15x22	1¾	8⅞x1¾	3	1—2	2-1½C & 1-1½NC	725	15x22
16x16	1⅝	8 x1⅝	3	1—1½	2—1½C	500	16x16
16x24	1⅞	9½x1⅞	3½	2—1½	4—1½C	925	16x24
18x18	1¾	8⅞x1¾	3	2—1¼	4—1½C	700	18x18
18x26	1⅞	10⅜x1⅞	3½	2—1½	4—1½C	1125	18x26
20x20	1⅞	9⅝x1⅞	3½	2—1½	4—1½C	925	20x20
20x30	2⅛	11⅛x2⅛	3½	2—1½	6—1½C	1525	20x30
22x22	2	10½x2	3½	2—1½	4—1½C	1150	22x22
22x32	2⅛	12⅛x2⅛	3½	2—1½	6—1½C	1850	22x32
24x24	2⅛	11⅜x2⅛	3½	2—1½	4—1½C	1425	24x24
24x36	2⅜	13⅛x2⅜	4	2—2	6—1½C	2425	24x36
26x26	2¼	12¼x2¼	4	2—1½	6—1½C	1800	26x26
26x38	2½	14¼x2½	4	2—2	6—1½C	2825	26x38
28x28	2⅜	13 x2⅜	4	2—2	6—1½C	2200	28x28
28x42	2⅝	15¼x2⅝	4½	2—2	8—1½C	3550	28x42
30x30	2¼	13¾x2¼	4	2—2	6—1½C	2525	30x30
30x45	2¾	16⅛x2¾	4½	2—2	8—1½C	4175	30x45

Note—"C" indicates gates connected to Pouring Gate. "NC" indicates gates not connected to Pouring Gate

Formula upon which foregoing table is based.

$$\text{Gap} = \frac{\sqrt[3]{\text{Area}}}{4} \text{ Thickness of collar at center; same as gap}$$

$$\text{Width of collar} \cdot \frac{3\sqrt{\text{Area}}}{10} + \text{twice gap.}$$

Diameters shown above for pouring gates are mean diameters. In practice these pouring gates should be tapered, bottom diameter approximately 1/8" less and top diameter approximately 1/8" greater than dimensions given.

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Cleaning.—The sections must be thoroughly cleaned. All oxide and scale from the cutting operation, as well as all dirt and grease, must be removed as far back as the mold box is to reach so that when the mold is rammed up there will be no grease to burn out during preheating which might leave a space between the mold and the parts to be welded.

Allowing for Contraction.—Allowance for contraction is made by setting the parts away from each other an amount sufficient to make up for the

Table 3—Details of Automatic Crucibles, Lining Materials, Cones, Stones and Thimbles

Size of Crucible	Capacity in Lb. Thermit	Outside Diameter at Top, In.	Height, In.	Size of Magnesia Stone for Relining	Size of Magnesia Thimbles to Be Used	Size of Plugging Material to Be Used	Weight of Magnesia Tar Required for Relining, Lb.	App. Gross Shipping Weight, Lb.
No. 1	6	8 1/2	8 1/2	No. 1	No. 1	No. 1	14	40
No. 2	8	9 1/2	9	No. 1	No. 1	No. 1	17–19	60
No. 2 1/2	10	11	11 1/2	No. 2	No. 2	No. 1	38–40	90
No. 3	15	11 1/2	13	No. 2	No. 2	No. 1	42–46	110
No. 3 1/2	22	12 1/2	14 1/4	No. 2	No. 2	No. 1	48–50	120
No. 4	25	13 1/2	15 1/2	No. 2	No. 2	No. 1	59–62	125
No. 5	35	16 1/2	16	No. 2	No. 2	No. 2	84–92	150
No. 6	65	19	19 1/2	No. 2	No. 2	No. 2	148–153	250
No. 6-A	90	23	21 1/2	No. 2	No. 2	No. 2	210–218	350
No. 7	125	24	23 1/2	Nos. 1 & 2	No. 2	No. 2	230–240	450
No. 8	175	26 1/2	27	Nos. 1 & 2	No. 2	No. 2	287–300	525
No. 9	250	29	29	No. 3 & 3 Spec.	No. 3	No. 3	337–345	650
No. 10	350	32 1/2	32 1/2	No. 3 & 3 Spec.	No. 3	No. 3	480–495	775
No. 12	800	38	36	No. 4	No. 4	No. 3	950	1250
No. 15	1500	44 1/2	42	No. 4	No. 4	No. 3	1100	1500

contraction of the weld when it cools. This distance may vary from $^1/_{16}$ in. to $^1/_4$ in. (in addition to the regular gap), depending on the size of the weld. In some cases, the increased space may be obtained by simply separating the parts and in other cases by forcing the sections apart with a jack or other mechanical means. In other cases, it will be necessary to expand by means of heat an opposite member to the section being welded.

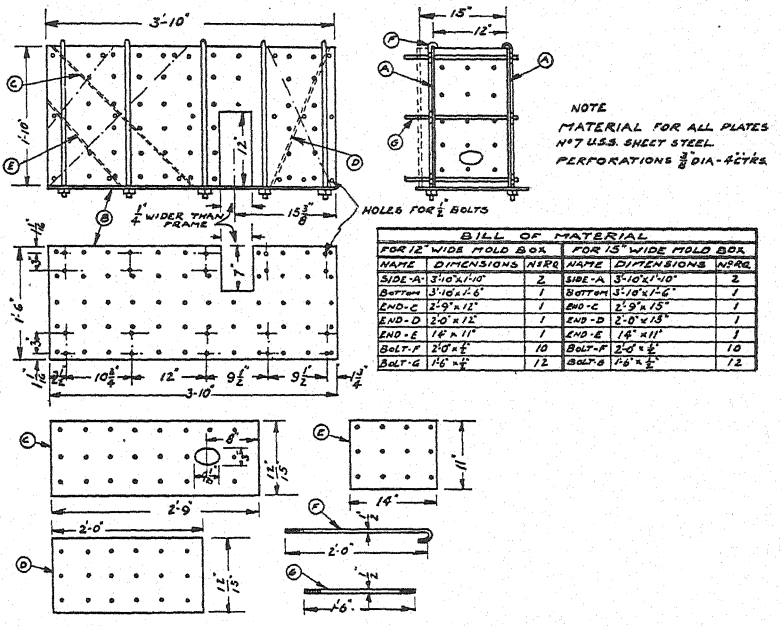
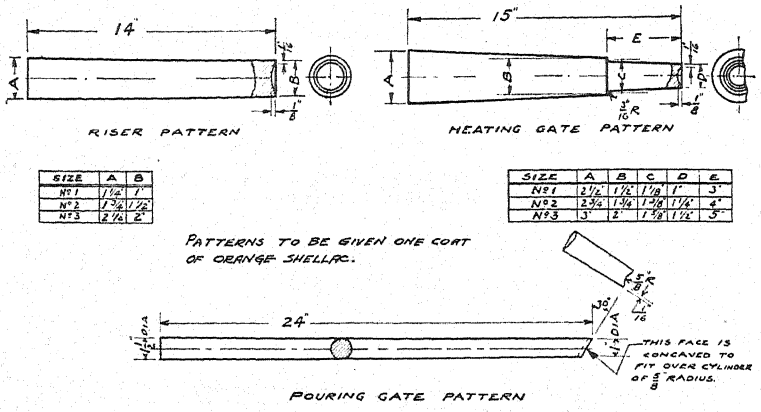


Fig. 4—Design and Materials Required for Standard Mold Box in Making Thermit Welds on Sections up to $6^1/_2$ In. x 8 In. in Size. Larger Mold Boxes Can Be Made in Proportion

Under certain circumstances, in order to confine the heat or to preheat other parts, a small fire brick or sheet iron furnace is built around the member being expanded. This, however, is done only at time of preheating. Care should be taken not to overheat for expansion, a black heat being sufficient.

In allowing for contraction of a Thermit weld, the actual contraction of the small amount of Thermit steel in the space between the pieces being welded is not the important factor for it must be remembered that during preheating the ends of the pieces at the fracture expand or approach each other by the amount of the expansion of the adjacent parts from the heat absorbed. Actually, the contraction at the weld may vary from $^1/_{16}$ in. to $^1/_4$ in. Allowing for such contraction is, however, a comparatively simple matter. For example, if the fracture is opened up $^1/_4$ in. to allow for contraction and if, during preheating, the parts approach each other almost $^1/_4$ in. due to expansion of adjacent members, the parts being welded

should be very nearly in line after welding. In welding large sections, relatively greater allowances are made for contraction than in smaller sections because preheating requires more time and consequently the heat is absorbed farther along the parts causing greater expansion and an increased tendency to close up the gap at the fracture.



SIZE	A	B
No 1	1 1/4"	1"
No 2	1 3/4"	1 1/2"
No 3	2 1/2"	2"

SIZE	A	B	C	D	E
No 1	2 1/2"	1 1/2"	1 1/8"	1"	3"
No 2	2 3/4"	1 3/4"	1 3/8"	1 1/4"	4"
No 3	3"	2"	1 5/8"	1 1/2"	5"

Fig. 5—Wooden Patterns for Pouring Gate, Riser and Heating Gate of Mold

Wax Pattern.—The next step is the making of the wax pattern, which is formed around the parts to be welded in the exact shape of the collar of Thermit steel desired in the finished weld. The opening between the ends of the parts is also filled with wax, as shown in Fig. 6. A vent hole, not shown in the drawings, is provided extending through the wax pattern from the preheating gate to the riser. A convenient way to do this is to imbed a 1/4-in. diameter cord in the wax. Pulling out the cord after the pattern has been formed leaves the required vent.

The pattern is made of yellow wax warmed until plastic.

Molds.—The mold box is placed in position and securely blocked up so that all weight is removed from the sections being welded. Figure 4 shows the design of the mold box.

In ramming up the mold a small amount of molding material is placed in the box and rammed hard, first around the edges and then in toward the center, the mold being kept level at all times. The material is packed as tightly as possible and care is taken that the parts underneath the pattern are all well rammed. Thickness of molding material from the edge of the collar need not be greater than the width dimension of the collar, and in many cases can be less, except at the end of the mold where the pouring gate is located, which end may have to be somewhat thicker.

Gate Patterns.—The wooden heating gate pattern is set at the lowest point of the wax pattern and leading out to the front of the mold box where an opening is provided for it. Where sections to be welded are of the same size, this heating gate is centered directly on the wax pattern. If a light section is being welded to a heavy section, however, the preheating open-

ing in the mold is directed more toward the heavy section in order to assure more uniform heating of the two sections.

With the heating gate provided for, another wooden gate pattern is set directly above it and placed 1 in. away from the wax pattern to provide a pouring gate. Drawings for various patterns are shown in Fig. 5.

In order that the molding material will not crumble under the blast of the preheating flame, it must be particularly well rammed around these patterns.

Riser.—Following the ramming around the heating and pouring gate patterns, a wooden riser pattern, as shown in Fig. 5, is placed at the highest point of the wax pattern and the mold box is then rammed up solid. If there is more than one high point a riser is required for each.

Riser for Vertical Welds.—In case of a weld on a vertical member, provision for supplemental risers above the weld is made in order to act as a vent and allow the Thermit steel to fill the mold completely.

Supplemental risers for vertical welds may be made by applying wax $^3/_{16}$ in. thick on the upper section from the top of the wax collar pattern to the level of the top of the mold. This forms an efficient vent at the top of the collar, as well as providing the desired riser, and the resulting thin slab of Thermit steel is readily cut away after the weld is completed (Fig. 6).

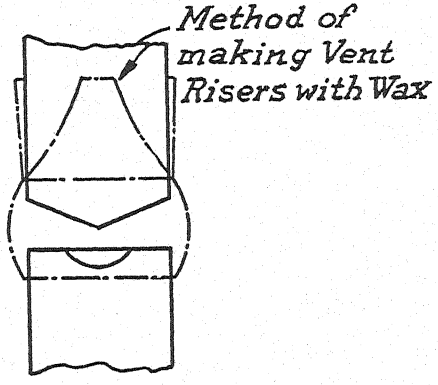


Fig. 6—Design of Riser for Vertical Weld

Venting of Mold.—When the mold is completely rammed, the top is hollowed out to provide a catch basin for the slag and the next step is to vent the mold thoroughly with a vent rod made from 8 to 10 gage wire. Venting is an important factor in that it permits the escape of gases from the liquid metal. Vent holes to be useful should not reach the wax collar.

Figure 7 shows diagrammatically a typical mold with risers, gates and vents.

Completing Mold.—Wooden patterns for the various gates and risers are removed after tapping them gently to loosen them and any loose sand that may have fallen into the holes is removed with a molder's lifter. The openings are then covered so that nothing may fall into them and the crucible, which has been plugged in accordance with directions given on

page 529, is placed in position with the bottom about 10 in. above and directly over the center of the pouring gate. Where the crucible cannot be so placed, a runner is constructed of molding material to lead the liquid steel into the mold.

Preheating.—Preheating is done with the usual Thermit preheating equipment, which blows finely atomized kerosene with compressed air into the heating gate, the mold acting as the combustion chamber.

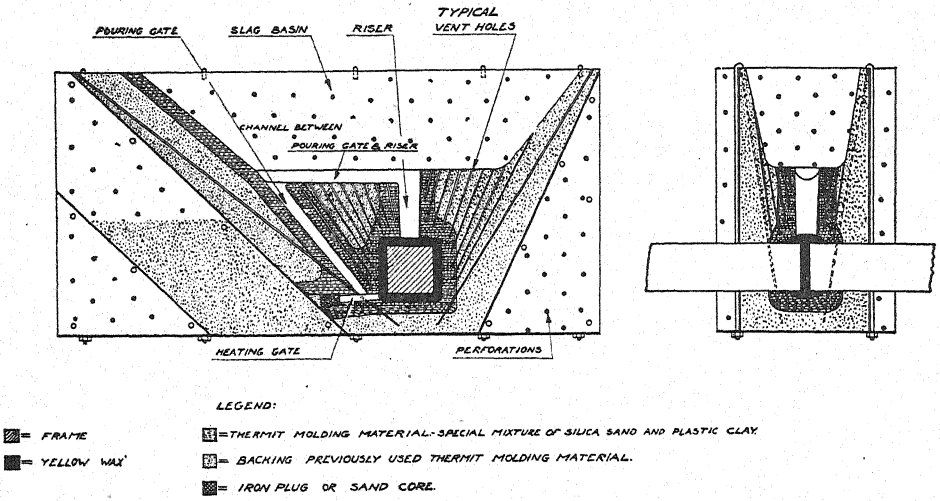


Fig. 7—Method to Be Employed in Constructing Molds for Making Thermit Welds and Materials Needed

In starting the preheating operation, the burner of the preheater is set to point into the heating gate but is placed about 1 in. away from the opening. The blast is applied gently at first to avoid cutting the mold while it is still damp. The wax pattern burns away, leaving a perfect mold the exact shape of the desired weld. Heating is continued until the mold is thoroughly dry and the parts to be welded attain a good workable heat. Regulation of the flame is accomplished by reducing or increasing the air pressure so as to make the hotter part of the combustion chamber at the lower portion or the upper portion of the weld, as required.

Preheating is extremely important and must be thorough. To test the heat, the burner is removed for a period of 1 to 4 min., depending on the size of the weld, and if parts are still red and no dark spots appear, it is safe to assume that sufficient heat has been absorbed.

Charging the Crucible.—While preheating is in progress, the crucible, which previously has been plugged, may be charged, as outlined on page 529. No ignition powder should be added until it is time to ignite the Thermit. If the Thermit charge comes higher in the crucible than 2 in. from the top or if it is necessary to tip the crucible, a ring, as shown in Fig. 8, is added to give more height to the crucible. This ring is sufficiently smaller in diameter than the crucible to permit its being set down into the crucible at

least 1 in. Such a ring is generally 8 in. to 24 in. high and requires luting with fire clay.

Plugging Heating Gate.—When the sections to be welded have attained proper heat, the preheater burner is quickly removed and directed down the riser for a moment or two, or down the pouring gate if the riser is inaccessible, in order to blow out any dirt or sand which may have fallen into the mold. The heating gate is plugged with a dry sand core, a piece of fire brick shaped to fit, or an iron plug, as shown in Fig. 9. This plug is backed with molding material, packed in hard between the outside of the mold box and a steel plate supported by rods in the mold box extension.



Fig. 8—Crucible Provided with Extension Ring for Holding Additional Quantity of Thermit

Igniting Thermit.—The Thermit is ignited by means of a special ignition powder. A small quantity of this powder (half a teaspoonful is ample) is placed on top of the Thermit in the crucible and the powder is touched off with a red-hot rod or wire. When a large quantity of Thermit is to be reacted, pour the ignition powder in several criss-crossed lines on top of the Thermit before igniting it. Reaction begins immediately and ample time must be allowed for its completion. Approximately 35 seconds after igniting the Thermit, however, it is safe to tap the crucible, as directed on page 529. Tapping the crucible permits the contents of liquid steel to run into the mold, and the alumina slag to run into the basin provided for the purpose on top the mold.

Continuing Expansion.—When contraction has been allowed for by jacking the pieces apart, the jack should be left in position until the Thermit steel has cooled sufficiently to take this load. Likewise, if expansion

has been obtained by heating a parallel member, heating should be continued until the weld begins to contract, when it can be stopped and the two parts allowed to cool together. The length of time that the jack or preheater burner may be left in place after making the weld depends largely on the size of the sections and the length of the preheating.

Annealing the Weld.—After making the weld, the weld metal may be thoroughly annealed by allowing the mold to remain in place overnight, or for at least six hours.

Finishing the Weld.—After removing the mold, the risers and gates are cut away with an oxyacetylene torch, and, in the case of shafts or similar parts, the collar of Thermit steel is machined off completely, if desired.

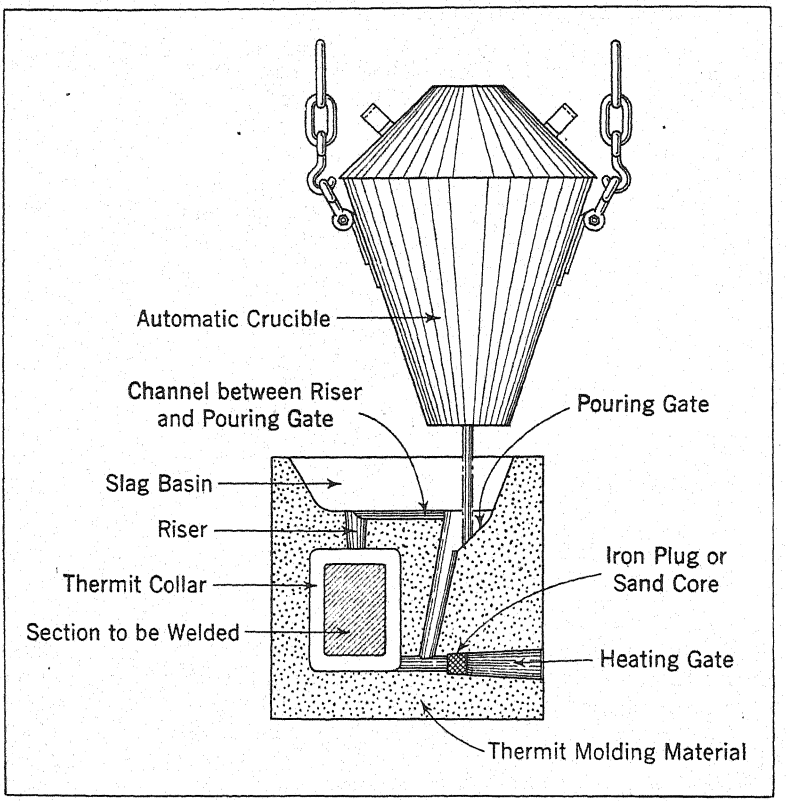


Fig. 9—Method of Plugging Heating Gate

Quantity of Thermit Required

The quantity of Thermit required for welding sections of different sizes is shown in Table 2.

Quantities may also be calculated, however, from the weights of the wax

patterns. When the supply of wax is weighed before and after making the pattern, the difference gives the weight of the wax used in the pattern. Then for every pound of wax used, the steel from 25 lb. of Thermit is required. When calculating by this method, it is, of course, essential that the entire space to be filled with Thermit steel should be filled with wax.

Calculating the quantity of Thermit in advance of making a weld is also possible by estimating the total number of cubic inches of space to be filled with Thermit steel and allowing three-quarters of a pound of Thermit for each cubic inch. This allowance provides sufficient steel for welds, gates and risers. The space between the ends of the sections is readily determined. In estimating the cubic contents of the collar, however, the simplest method is to multiply the width of the collar by its greatest thickness and then to multiply the result by 0.7 to determine the average area of cross-section. If this figure is then multiplied by the total length of the collar around the part to be welded, and if all measurements are made in inches, the result will be the cubic inches in the collar.

CRANKSHAFT REPAIRS

In the repair of crankshafts, and other shafts, including rudder stocks and cross heads, the important feature is the proper control of contraction and other factors which may lead to misalignment or defects after welding.

Alignment.—Such repairs may be made with the aid of supporting blocks. The longer end of the shaft is clamped rigidly in place while the shorter end, left free to move in the line of the weld, is set at such a distance that, when the weld cools and contracts, the short end of the shaft is drawn back into approximate alignment. In such work it is usual practice to substitute a new short end slightly larger in size than the original end. After this new end is welded on, it is machined down to the proper diameter and any slight misalignment is automatically corrected.

The Use of "V" Blocks.—Greater accuracy in alignment is attained, however, with less machining when "V" blocks are used in aligning shafts for welding. These "V" blocks are heavy, accurately machined pieces, which slide in the machined slot of a heavy bed plate. The blocks are spaced along the slot of the bed plate at intervals corresponding with the journals of the crankshaft. Parallel to the main slot of the bed plate and on either side of it are smaller slots, similar to those in planer beds. The heads of holding-down bolts are placed in these slots opposite the "V" blocks and short bars or channels are placed across the shaft and clamped down by means of nuts on the holding-down bolts.

The "V" blocks are so spaced on the main journals that the shaft may slide $^1/_4$ in. in either direction parallel to its axis without a shoulder or crank throw striking any part of the blocks. Shafts are usually lined up with the throws horizontal. When the break is in the pin journal, however, the webs should be in a vertical plane with the broken pin journal lowermost. The purpose of placing the pin journal lowermost is to bring the riser up between the two webs so that it will shrink sidewise about the same amount as the journal and the molding material will not interfere with the contraction of the welded journal.

If a shaft has a break in one slab or throw close to the pin journal, it is lined up in special "V" blocks, as shown in Fig. 10. These blocks allow a horizontal motion during the heating and cooling of the shaft. When proper allowance is made, the shaft comes back into position because the force tending to separate the fracture is not resisted and is subsequently counteracted by an equal contraction.

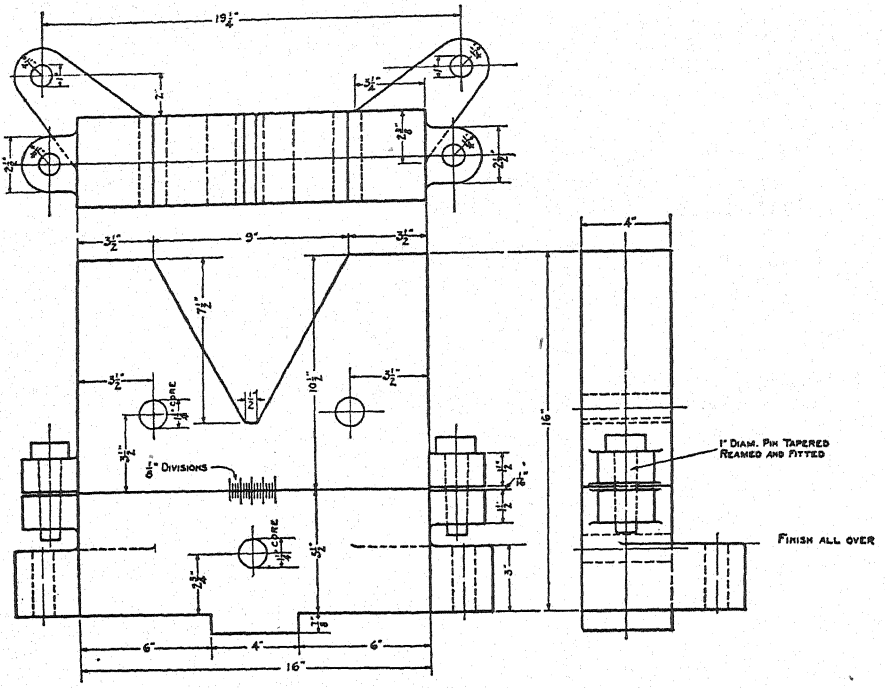


Fig. 10—Showing Proper Design for V Blocks for Thermit Welding Crank Shaft

Design of "V" Blocks.—"V" blocks are made in such a way that they will divide in two parts horizontally. Upper and lower sections each have divisions accurately marked on them along the dividing line. When the two parts of a "V" block are central on each other, accurately turned taper pins may be inserted in the reamed holes through the lugs in order to fasten the upper and lower sections together. The central position is thus located accurately for the purpose of aligning the shafts "in line." Where a transverse contraction is to be allowed for, however, pins are left out of certain "V" blocks and the slabs of these blocks are shifted as required. Where "V" block pins are not in place the holding-down bolts are relied on to hold the shaft in place during the ramming of the mold. As soon as preheating starts, however, these bolts are removed from such "V" blocks so that the shaft may move freely.

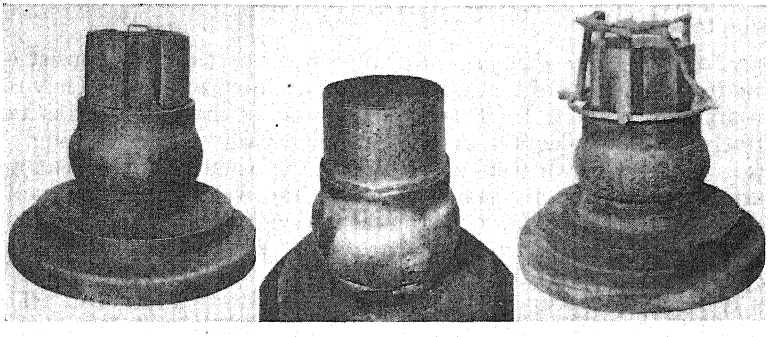
STEEL MILL REPAIRS

The inherent advantages of the Thermit welding process, particularly

where heavy sections are involved, have led to its being largely used in the iron and steel industry, as an emergency repair method, as a means of salvaging broken parts from the scrap pile and for the fabrication of heavy parts.

Among the most common applications for Thermit welding in this field are welding new necks to rolls and pinions, the welding in of new pinion teeth to replace teeth broken out in service, the building up of worn wabbler ends of rolls and pinions, the repair of fractured mill housings, charging peels and shafts and the repair of heavy parts in general.

Welding Necks on Rolls and Pinions.—Where the neck is broken off a roll or pinion, it is generally more satisfactory, instead of welding the broken piece back on, to replace it with an entirely new piece. The new part, which is cast or forged slightly oversize, is welded on in the usual way and then machined to proper diameter and alignment.



A B C

Fig. 11—Welding Necks on Rolls and Pinions

A. Showing welded neck and wooden pattern in place.
B. The molten wax is poured into the space between the wooden patterns and remaining parts of wabbler ends.
C. The completed weld before removing pouring gates and risers—no machining necessary.

Building Up Worn Wabblers.—Where wabblers are badly worn away or battered, it is best to cut away the worn section and weld on a new neck. If the wear is not too great, however, the worn parts may be satisfactorily rebuilt with Thermit steel. Wabbler Thermit, especially designed for this purpose, is used and the resulting deposited metal, while machinable, is sufficiently hard and tough to provide longer wear than the original metal in the piece. In building up a worn wabbler, it is necessary, first, to provide a wax pattern, representing the metal to be replaced. Either one of two methods may be employed in making this pattern. One method consists of, first, making a wooden pattern, as shown in Fig. 11, which exactly fills the spaces between the pods in a new wabbler. These wooden pieces may be dimensioned either from new rolls or from the patterns from which the rolls are cast. With them in place between the pods of the worn wabbler, the wabbler end is surrounded with a piece of

sheet iron and molten wax is poured into the spaces, representing the metal worn away in service between the wooden patterns and the worn wabbler ends. The wooden patterns are then removed, a sand mold is rammed up and the parts are preheated and this molten metal poured in the usual way.

The alternative, and somewhat more satisfactory method, is to make a mold for casting out of portland cement and plaster of Paris. This mold is formed around the end of a wooden pattern corresponding to a new wabbler of the same dimensions as the one to be repaired. This is allowed to overlap the end of the roll or pinion so that when placed in position on the worn wabbler, it will center itself. After this mold has been put in place, the open spaces are filled with molten wax in the same way as when the wooden patterns, described above, are used.

Both wooden patterns and plaster of Paris molds are permanent equipment and may be used over and over again. In fact, it is usual practice for a steel mill welding department to carry in stock several different sizes of molds or patterns to fit the various size wabbler ends which they may have occasion to repair.

New Teeth in Large Pinions.—Repairs of this sort usually consist of replacing teeth, or parts of teeth, which have been broken out. They represent a different problem than the ordinary weld in that the tooth is a comparatively small projection on an extremely heavy steel casting. For this reason, if the repair were attempted in the usual way, the heat would be carried away from the point at which the weld was being made so quickly, particularly during the interval of removing the preheater burner and tapping the crucible, that in many cases no weld would result. Everything possible, therefore, must be done to conserve the heat at the weld and it is usually necessary to heat the entire pinion to a red heat. This is done by bricking in the heavy parts and preheating with oil or gas burners, operated in conjunction with the regular preheater, while the preheating for the weld is under way. Care must be taken, however, to bring up the heat slowly as otherwise there is some danger of cracking the pinion.

Furthermore, in all welds in which a small quantity of Thermit steel is added to a heavy casting, special precautions must be taken to secure thorough amalgamation of the Thermit steel with the heavy part, especially at the edges of the line of junction, where, in service, the greatest strains occur. Even the slightest imperfection at this point will cause a tear to start and result in fracture at the weld. A perfect weld on this extreme fiber is difficult to accomplish because of a slight difference in shrinkage after a weld is poured between the molten Thermit steel and the white-hot steel of the pinion. Full fusion for a considerable depth, even at the

Fig. 12—Preliminary Steps in Welding Teeth in Pinions (*Opposite Page*)

A. Section through broken tooth, showing usual line of fracture.
B. Showing method of cutting shroud and attaching board and clay luting for welding shroud.
C. Sand core rammed to form mold for one-half of tooth.
D. Both cores in position and filled with wax.
E. Design for board to support bottom of sand cores.
F. Section and elevation of sand cores used as one-half of wax pattern mold.
G. Mold box applied.

A
B
BOARD OVER SHROUD RING
CLAY LUTING
A
C
TOOTH BROKEN OUT HERE
B LESS ¼"
SCRAPE OFF ¼ FROM SAND
D
WAX CUT UP INTO SMALL CUBES
E
HEIGHT OF TOOTH
LENGTH OF BOARD = A LESS ¼"
B LESS ¼"
BOARD USED AS BOTTOM OF SAND CORE
F
G.
MOLD BOX
1803

extreme edges of the Thermit steel, is, therefore, essential and for this reason it is desirable to have as large a surface as possible exposed to the Thermit steel. This is accomplished by placing the pinion in a planer and machining out a slot in the main body of the pinion along the center line of the area where the tooth has been broken out. This slot is made half the width of the tooth and approximately the same depth, that is, if the tooth to be welded is 6 in. wide at its root, the slot is machined 3 in. wide and 3 in. deep. Another purpose of this slot is to produce edges or corners which melt readily and aid in the fusion.

Patterns are constructed and fitted, as shown in Fig. 12. A pair of sand cores mounted on boards is made by placing the boards in the spaces between pairs of adjacent teeth and ramming these spaces full with molding material. Lag screws in the boards permit easy handling of the cores.

The pinion is up-ended and mounted in an excavation on a solid foundation and the cores are placed in position on either side of the machined gap. The space between the cores is filled with molten wax to provide the pattern for the new tooth. After the wax has hardened, the cores are removed and the mold box is fastened securely to the pinion by metal straps bolted to the mold box and insulated from the pinion by 3 in. of sand and fire clay rammed in solid between pinion and straps. The mold is rammed with the usual gates, risers and vents, care being taken that the heating

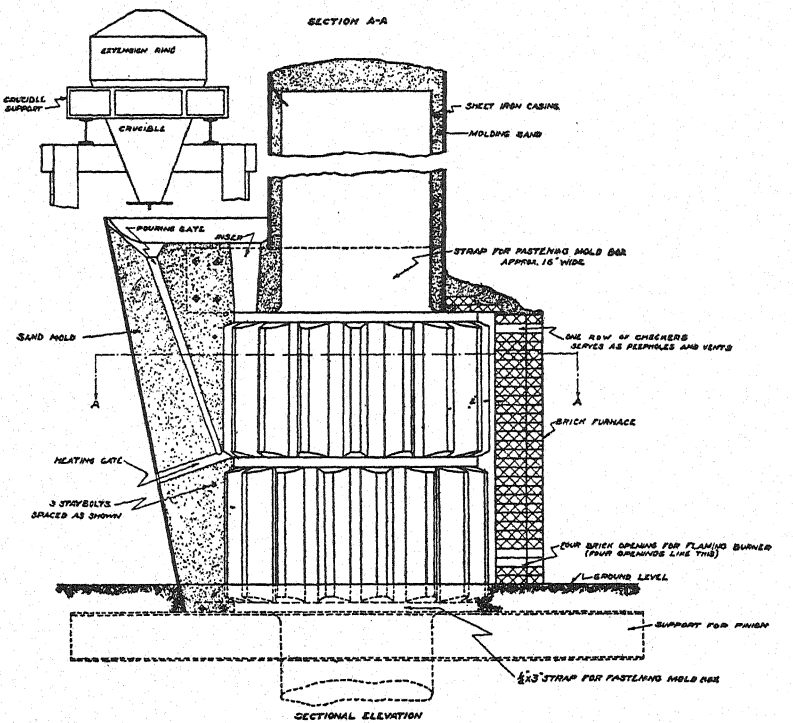


Fig. 13—Method of Setting Up Mold Box and Brick Furnace in Pinion Tooth Welding

gate, the inner end of which connects the pouring gate to the weld, is at the lowest point of the weld.

When this operation is completed, a brick furnace (Fig. 13) is constructed around the exposed part of the pinion, clearing the tooth by about 2 in., and a sheet-iron casing is placed around the exposed neck. This casing is 6 in. larger in diameter than the neck and about 4 in. higher. It is rammed full of sand to provide insulation for the neck.

The next step is preheating. A burner is placed at the bottom of the brick furnace and preheating is started with a very mild heat to avoid too rapid expansion of the pinion. After the pinion has been thoroughly soaked with heat, however, the burner is opened up and heating is continued until the entire pinion reaches a good red heat or approximately 1200°F. temperature. Pouring of the weld is done in the usual way.

RAIL WELDING ON STREET RAILWAYS

The welding of street railway rails has proved one of the fields of greatest usefulness for the Thermit process. Standard practice for the past twenty-five years of most of the street railways in the United States, Thermit welding, by eliminating rail joints, effectively prolongs rail life and does away with joint maintenance.

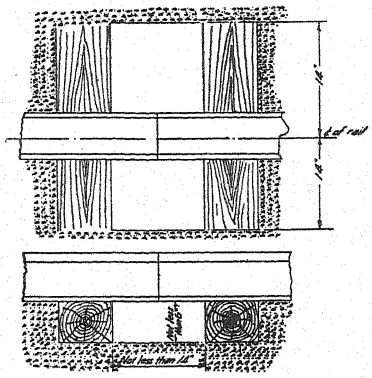
In the welding of rails with Thermit, the same general procedure is followed as in other work. Through simplification, such as the use of permanent patterns, and other refinements, however, the process has been adapted to the making of quantities of identical welds on practically a production basis.

Broadly speaking, there are two methods by which Thermit welds are made on street railway rails: one is with the use of inserts, while the other involves undercutting the rail ends.

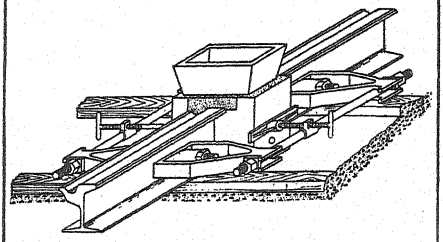
Inserts.—In the insert method, an insert cut from a piece of rolled steel, having the same analysis as the rail itself, is placed between the rail heads at the running surface. The liquid Thermit steel, poured into the gap between the rail ends below the insert, fuses with the webs and bases of the rails and the bottom and sides of the insert and makes a fusion weld of these portions. At the same time, the insert and the ends of the rail heads are brought to welding heat and the expansion of the rails from the intense heat of the weld, as well as the contraction of the Thermit steel as it cools, causes the rail ends to exert tremendous pressure against the insert and results in a partial butt weld of rail heads and insert.

Undercutting.—Where undercutting is employed, no inserts are used but rail heads are butted tightly together and a gap is cut in the webs, bases and lips of the rails at the joint to provide space for the fusion part of the weld. An additional gap cut in the outside surface of the rail heads extends the fusion-welded portion on the outside of the head beyond the running surface. The overhanging portions of the rail heads actually form an attached insert and are butt welded in much the same way as when a separate insert is used.

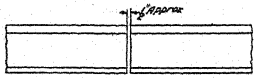
The design of the Thermit rail weld for street railways and the equip-



1- Open up pavement as shown.

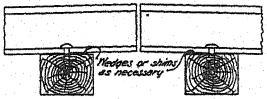


Welding loose rails under traffic, the necessary pressure that prevents the relative motion of the rail ends under load is exerted by the use of compression clamps as shown by above illustration.

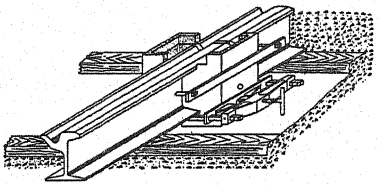


2- Cut approximately 1/8" gap where necessary between rail ends, cutting through head with a saw and through the web and base with a torch.

3- Clean rail ends thoroughly removing all dirt and rust at least 3" either side of joint.



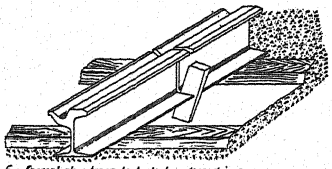
4- Tighten rail ends to ties adjacent to joint by shimming between rail and tie if necessary at same time raising joint to required height to insure correct surface after welding and grinding.



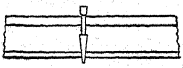
8- Special molds applied which do not interfere with operation of cars. Molds must be carefully luted. Molds secured with special clamp through standard bolt holes and by regular square clamp at bottom.

9- Rail preheated from outside to avoid interference with traffic. Iron cap placed over mold top between cars to assist in heating heads of rails.

10- When rail is heated burner is withdrawn, vent hole plugged and strips of asbestos laid in groove of rail at joint and molding material tamped and trowelled into groove to the level of head and lip then heating burner is replaced.

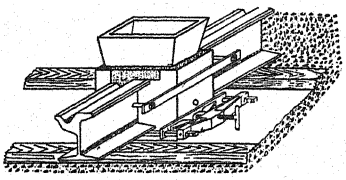


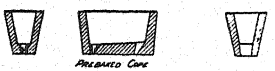
5- Special slow-taper tool steel wedges driven in with sledges between bases each side to open joint as far as possible.



6- Slightly oversize insert selected, heralled a little with a hammer along bottom edges and driven between heads.

7 Base wedges knocked out. The compression on insert if work has been done properly should be sufficient to hold weight of car.





11- A prebaked cope made on a special pattern is next put into place and molding material packed around the base of the cope. At the same time the fully charged crucible is mounted in position.

12- The preheating hole is then plugged and the weld poured in the usual manner. In two or three minutes the cope can be pried off and a car permitted to pass. The flange of the wheel automatically cleaning the sand from the groove.

Fig. 14—Steps in Making Thermit Rail Weld Under Traffic

ment employed have been perfected to the point where it is possible to weld rails during the day on busy streets without interrupting traffic. Cars continue to operate over the track being welded throughout the entire process except for a short period during which the Thermit reaction takes place and the weld is poured. Either inserts or undercutting may be employed in welding under traffic.

Briefly the successive steps in making a weld under traffic are as follows:

1. Where the undercut method is being used, cut away 1/4 in. of the base, web and lip of each rail end with a cutting torch. Butt the rails tightly together and where they join cut a 1/2-in. half-round notch vertically through the full depth of the outside portion of the heads.

2. Thoroughly clean about 3 in. of the end of each rail. Chip away burnt iron and oxide with a chisel. Use a wire brush on the tops, sides and bottoms. File and sandpaper the ends. Use sand blast on very old rails.

3. Tighten rails to ties and raise joint slightly with shims or wedges to assure good surface after welding and grinding.

4. Put joint under compression by wedging, or by applying large rail clamps. When clamps are not used, drive a slightly tapered wedge between rail bases at ends, hammer in insert and then knock out the wedge. The purpose is to lock the rails together so that they must move in unison and so that passing cars cannot cause independent motion of the rail ends.

5. Make the molds and cope, ramming in the molding material thoroughly and carefully. The molds for under-traffic welding are so designed that cars may pass over the joint after they have been applied to the rail.

6. Attach molds to rail, making sure that each is on the proper side of the rail and centered correctly. Tighten the molds against the rail either with an underslung clamp or with strut clamps attached to the heavy rail clamps.

7. Lute carefully all around the molds.

8. Preheat the rail ends until the entire rail section within the molds is a bright red. Keep the cast-iron heating cover on top of the molds all during preheating except to let cars pass or to dry the cope.

9. During preheating, plug and charge the crucible and dry the cope. Thermit for rail welding is packed in portions of various sizes, each sized portion containing the proper quantity of Thermit to make one weld on a rail of prescribed section. To dry the cope, remove the heating cover from the molds and put the cope upside down in its place for several minutes.

10. When preheating is completed, plug the vent in the inside mold and the heating gate in the outside mold, place the cope on top of the molds and lute carefully all around the cope.

11. Set the crucible stand in position with the tapping pin of the crucible directly over the 45° slope leading to the pouring gate in the cope.

12. Ignite the Thermit and in about 30 seconds tap the crucible.

13. When the liquid steel and slag have all run out of the crucible, set the stand to one side.

14. Allow two or three minutes for the weld to cool slightly, then pry off the cope and clean out the groove on groove rail.

15. Remove mold boxes and, with a hot chisel, cut away any excess metal from groove and running surface of rail.

16. While weld is still hot, hammer the riser and the top of the insert carefully to reduce subsequent grinding.

17. Finish grind the gage face and rough grind the surface with a wheel grinder. Finish grind the running surface with a reciprocating grinder.

The various steps in the making of a Thermit rail weld on street railway rail are shown in Fig. 14.

RAIL WELDING ON STEAM RAILROADS

One of the most recent developments in Thermit rail welding is in the railroad field, where the tendency is toward greatly increased operating speeds, and where the rail joint problem has become acute both from the standpoint of safe operation and from that of maintenance expense. The railroads are giving more and more consideration to the possibility of using continuous rails in main line track. While more or less experimental in nature, a number of installations of continuous rails, made up of quantities of standard rails Thermit welded into long, jointless stretches, are proving that the difficulties that were anticipated from expansion and contraction are by no means serious. In fact, with the type of track fastenings employed in the installation of these long rails, it is found that continuous rails, a mile and more in length, have little greater movement at their ends between winter and summer than individual 39-ft. rails.

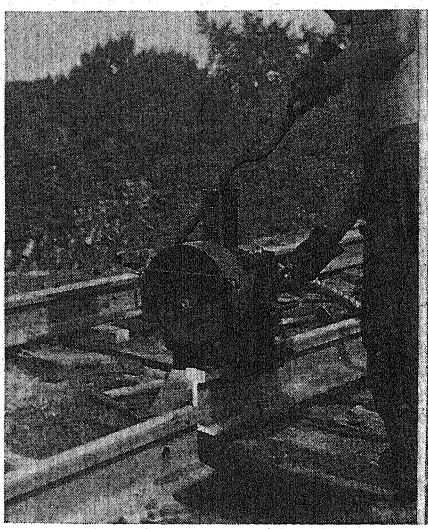


Fig. 15—Preparing Rail Ends

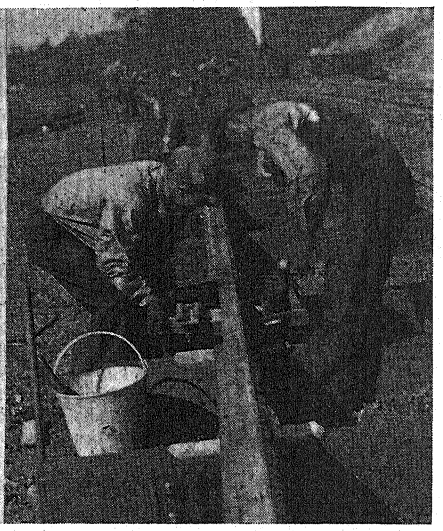


Fig. 16—Lining Up Rails

Pressure Fusion Weld.—The type of Thermit rail weld used in welding steam railroad rail is known as the pressure fusion weld. In this type of weld the bases and webs of the rail are fusion welded while the heads are welded by pressure alone and a full butt weld of the rail heads is assured.

The principal reason for the use of different designs of rail welds in street railway and in steam railroad work is the difference in operating conditions. Where track is paved, as in the majority of street railway track, there is little tension stress at the top of the rail joint so that a 100% weld on the head of the rail is not important. The main object is to provide a weld which is strong enough for the purpose and which, at the same time, is easy of installation under the conditions met with. The insert or undercut weld used on street railways with its partial butt weld of the rail heads is the easiest of all Thermit rail welds to install and produces a joint which has ample strength for the service. With standard railroad track, however,

where the rail carries much heavier loads and where the substructure is not so rigid as in paved track, a reverse bending stress occurs on the head of the rail and places the top of the joint in considerable tension each time it is subjected to a passing wheel load. A full butt weld of the rail heads is, therefore, essential.

In making the pressure butt weld, heating of the heads to welding temperature is brought about by means of the slag from the Thermit reaction. The molds are so constructed that this slag completely surrounds the heads at the joint when the weld is poured. Pressure for butt welding is obtained by means of rail clamps, which are drawn up to squeeze the rail heads together when they have been sufficiently softened by the heat of the slag.

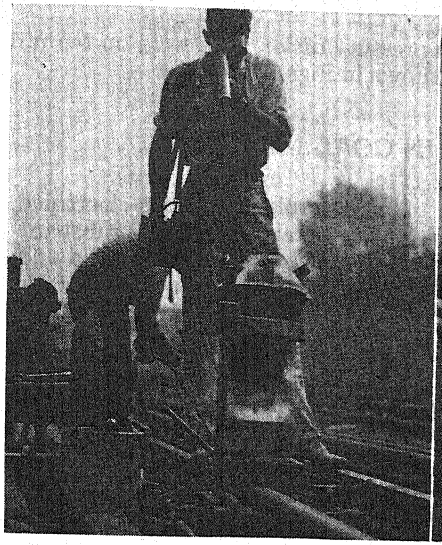


Fig. 17—Measuring Temperature of Rail During Preheating

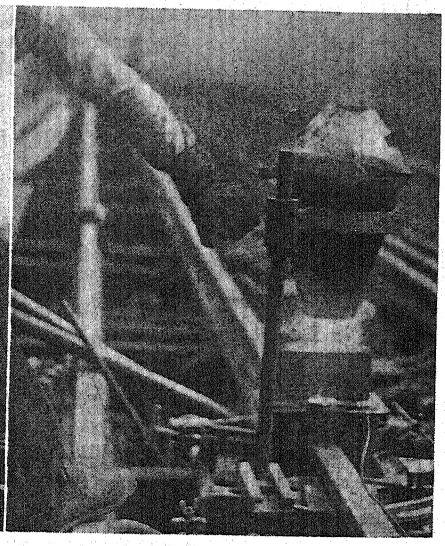


Fig. 18—Pouring the Weld

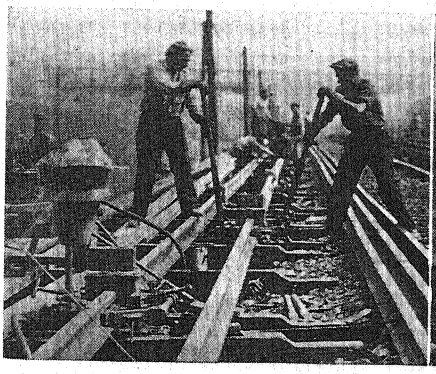


Fig. 19—Drawing Up on Rail Clamps

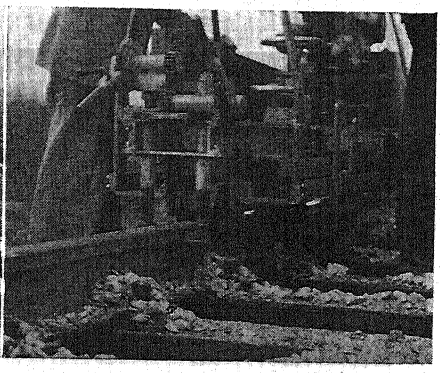


Fig. 20—Grinding the Completed Weld

Actual procedure, with the exception of applying and drawing up the rail clamps, follows closely the procedure used in the standard method of welding street railway rail. In applying rail clamps, rails with the vertical surfaces of the ends of the heads and upper parts of the webs ground and the lower parts of the webs and the bases undercut to provide a $^1/_2$-in. gap, are first carefully aligned; the clamps are fastened to the rail ends and tightened to force the rail heads together under pressure. After the molds are in place and preheating is completed, the liquid Thermit steel is poured into the mold and a period of about two minutes is allowed to elapse in order to permit the rail heads to become thoroughly soft at the ends. Clamps are then drawn up, forcing the softened rail heads together and producing a butt weld. The resulting upset of the rail heads is later ground off the running surface and the sides of the rail head to bring these surfaces to the original contour of the rail.

The various steps in the making of a pressure fusion butt weld on tee rail of standard steam railroad track are shown in Figs. 15 to 20.

RAIL WELDING IN COAL MINES

In coal mines, where the majority of main haulage track is electrified, maintenance of rail joints and bonds is an important item. By substituting Thermit welds for rail joints, this maintenance expense is avoided and, at the same time, because of the improved electrical conductivity of the rails, power consumption is reduced appreciably.

Thermit welding of coal mine track is carried on in exactly the same way as in the standard method of welding street railway track.

Because of the generally restricted working space available and the lighter weight rails encountered, however, the equipment employed in mine work has been scaled down and preheaters, clamps, mold boxes and crucibles are all considerably smaller than those used in the open.

MAKING SPECIAL WORK

An interesting and important additional application of Thermit rail

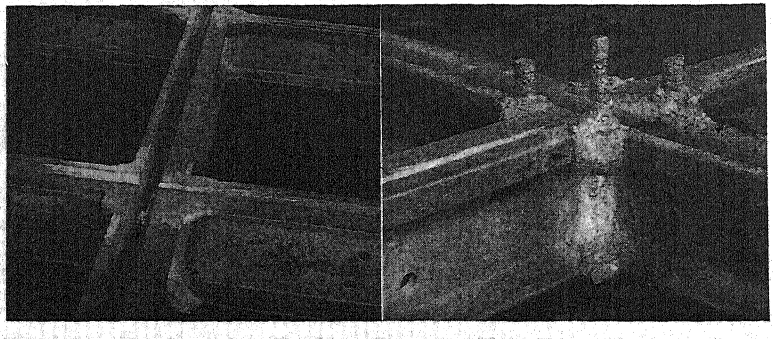


Fig. 21—Completed 90° Frog and Method of Welding

welding is the making of frogs, mates and crossings out of short lengths of rail welded together into desired designs. Even elaborate pieces are readily fabricated in this way, using the same equipment and methods that are employed in track welding.

Special work of this type is economical to fabricate and is amply rugged (Fig. 21). Compromise joints (Fig. 22) may also be made in this manner and have the advantage of being continuous pieces of rail varying in section rather than complicated and comparatively costly mechanical joints.

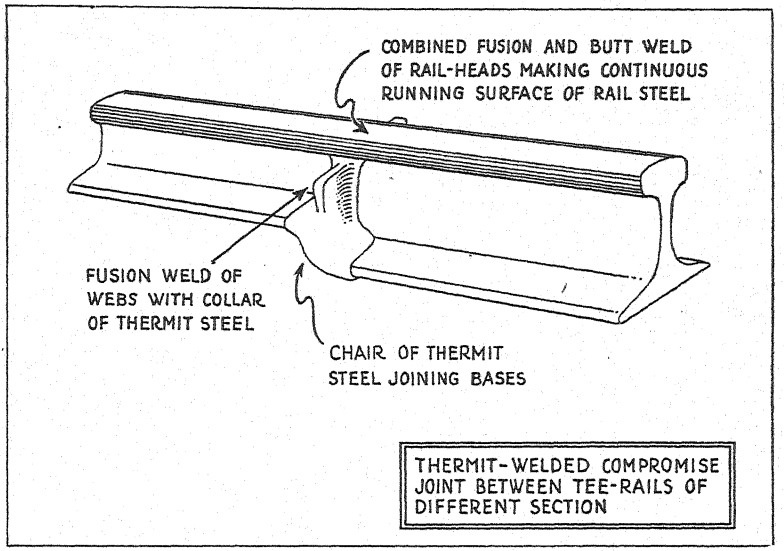


Fig. 22

Where only an occasional piece of special work is to be fabricated, wax patterns are used rather than the permanent patterns used in track welding. Molds are rammed on the rail very much in the same way as in making a Thermit repair to a shaft or machine frame. When a number of pieces are being made continually, however, the procedure is readily reduced almost to a manufacturing basis through the use of sets of permanent patterns designed to fit various rail sections and adjustable to different angles of intersection.

LOCOMOTIVE REPAIRS

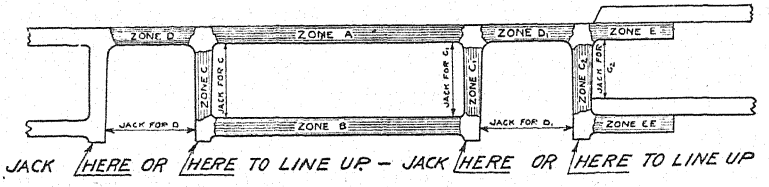
Locomotive repairs made by the Thermit process include repairs to broken frames, driving wheel spokes and the like.

This work differs little from general repair work except that in most cases the sections to be repaired are members of more or less complicated castings or forgings and in order to maintain proper alignment, careful attention must be paid to the control of expansion and contraction during welding.

In welding driving wheel spokes, the usual method of expanding the gap is to heat the unbroken spokes of the same segment so as to open the gap by $^3/_{16}$ in. to $^1/_4$ in. as measured by tram marks.

In frame welding, on the other hand, the use of jacks is generally more convenient. These are applied as shown in Fig. 23.

Where a frame is broken in the splice, the general practice is to make the repair not only so that the broken sections are welded together but also so that the broken section is welded to the unbroken one. This is accomplished by cutting out a piece from the unbroken member about 1 in. by 5 in., as indicated in Fig. 24, so that the Thermit steel flows entirely around the fractured part and, at the same time, fuses with the other member. This cut is made either by drilling or by means of an oxyacetylene torch.



Fracture Location	Remarks
Zone A	Jack at D to open gap at break. Place jack on a line with upper edge of member Zone B. Heat Zone B to get $^3/_{16}$-in. to $^5/_{16}$-in. expansion as determined by tram marks on each side of fracture in Zone A. Remove this heat when, or shortly after, the weld is poured. Preheating is done with flaming burner, or with basket fire. To avoid distortion of pedestal legs, pedestal braces should be in place.
" B	See above.
" C, C_1 or C_2	Jack at C, C_1 or C_2 to open fracture, $^3/_{16}$ in. to $^5/_{16}$ in. and hold about half an hour.
" D or D_1	Jack at D or D_1, to open fracture, $^3/_{16}$ in. to $^5/_{16}$ in. and hold about half an hour.
" E E	Cut out unfractured member of splice to clear collar.

Fig. 23—Method of Preventing Unequal Stresses When Welding Frames Which Are Broken at Various Points

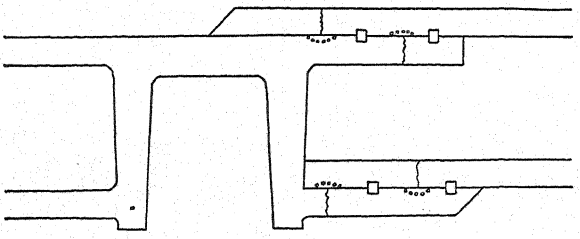


Fig. 24—Showing Method for Drilling and Cutting Unbroken Member for Splice Weld

CAST-IRON REPAIRS

The Thermit process, while entirely suitable for the welding of cast iron, cannot be used on all work of this nature because of the difficulty under certain conditions of allowing properly for the shrinkage of the weld metal when it cools. Contraction of Thermit steel is approximately double that of cast iron so that, generally, if the length of the crack to be welded is more than eight times the thickness of the section, the difference in shrinkage along the line of fracture will result in small hairline cracks in the weld. These cracks, however, appear perpendicular to the line of the weld and are not always of great importance so far as strength is concerned.

Special cast-iron Thermit is used for this work, consisting of plain Thermit, with which is mixed ferrosilicon and mild steel punchings in prescribed quantities. This type of Thermit produces a soft and homogeneous metal in the weld.

Because of the higher carbon content, cast-iron welds are also more difficult to machine than welds of wrought iron and steel. Grinding, rather than machining, is the usual method of finishing.

MARINE REPAIRS

The Thermit process is used extensively in the marine field for welding broken stern posts, stern frames, rudder frames, rudder posts, shafts and propeller struts. It has been approved by all leading underwriters for this class of work.

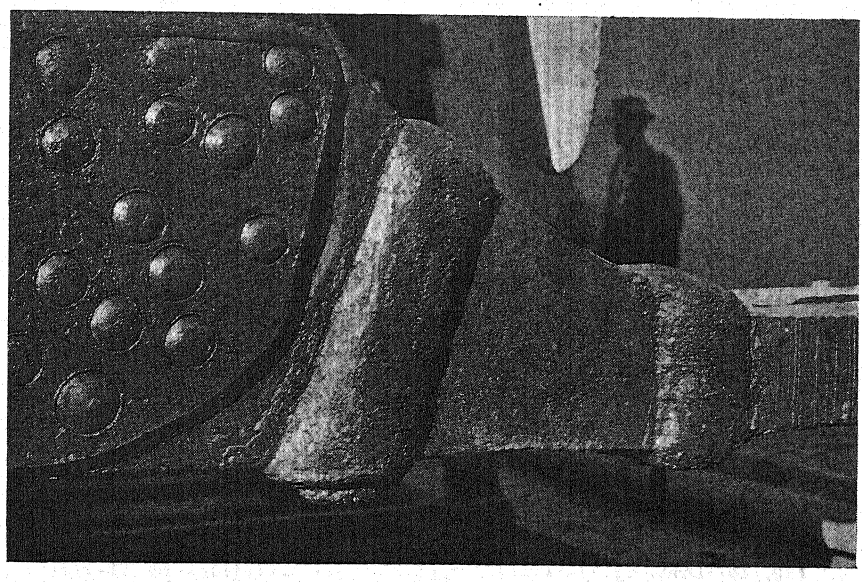


Fig. 25—Typical Marine Repair

The methods employed are similar in every respect to those used in general repair work and usually consist of welding at the point of fracture. In some cases, however, where there is more than one break, or where considerable defective metal must be replaced, it is desirable to install a new

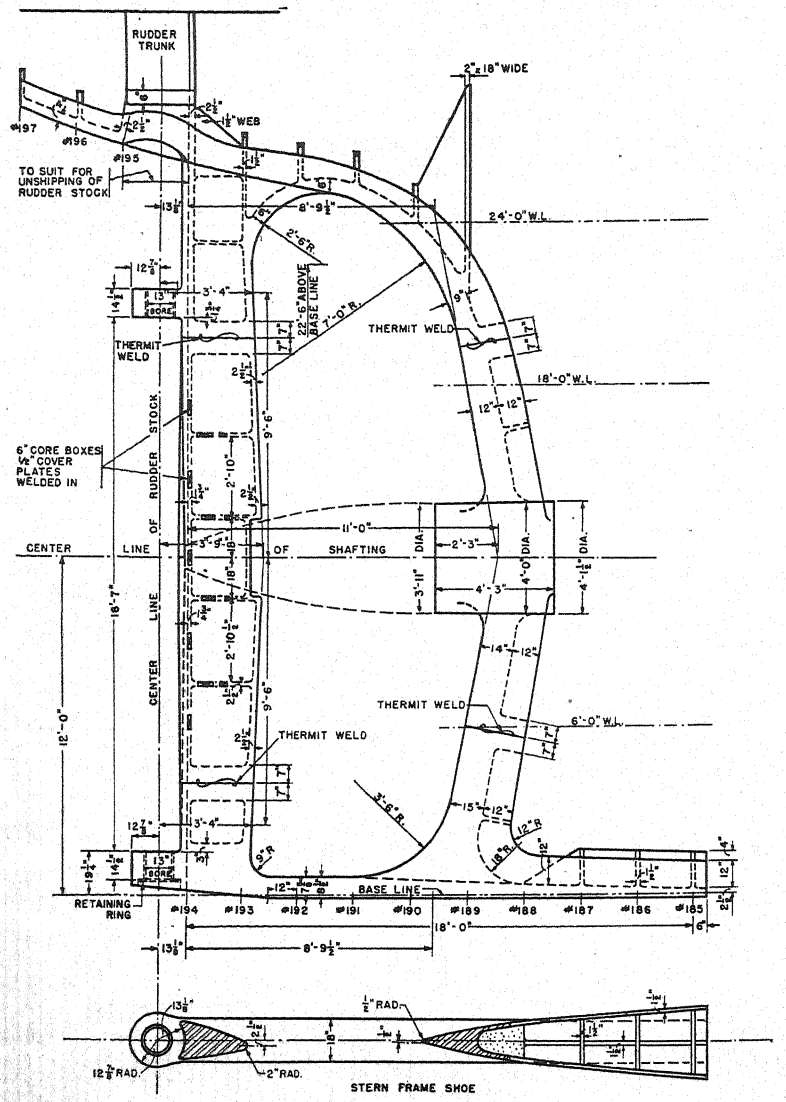


Fig. 26—Drawing Showing Dimensions and Locations of Thermit Welds in Fabricated Stern Frames for U. S. Maritime Commission Ships

billet or forging to replace the defective part. The new section is simply welded in place by means of two Thermit welds.

Figure 25 shows a typical marine repair.

NEW CONSTRUCTION IN THE MARINE FIELD

In addition to repair work, the Thermit process is also used in the marine field for the fabrication of heavy parts. The stern frames of a number of the several hundred cargo ships now being built for the U. S. Maritime Commission, for example, are fabricated in this manner. Ships classified as C-1, C-2 and C-3, as well as "Liberty Ships" which are to be equipped with contra-rudders for greater speed, have stern frames made in four sections, Thermit welded to form the complete frames (See Fig. 26). The Thermit welding of these frames as compared with a mechanized type of joint, or, for that matter, with electric welding, results in the elimination of a considerable amount of machining and gives a corresponding saving in time and expense.

CHAPTER 14A

BRAZING*

Definitions, Metals That Can Be Brazed, Brazing Materials, Fluxes, Procedures, Physical Properties of Completed Joint, Applications.

Definitions

BRAZING is technically understood to mean the joining without fusion of iron, cast iron, steel, copper, brass, bronze, nickel and other metals in similar or dissimilar metal combinations by means of a nonferrous filler material. "Brazing" is probably a corruption of the term "brassing," the implied original name of the operation wherein a strip of brass was placed between two metallic parts and heated in a forge to a temperature high enough to cause the brass to flow and form a strong bond between the parts.

The scope of brazing has been broadened by improved filler rods and the use of the oxyacetylene flame or any one of numerous electrical heating methods to a point where it now ranks in importance with either gas or arc fusion welding. Figure 1 shows in simple form the temperature range of various brazing processes with relation to other metal joining methods.

Brazing is usually defined as *a group of metal joining processes wherein the filler metal is a non-ferrous metal or alloy whose melting point is higher than 1000°F., but is lower than that of the metals or alloys being joined.*

Bronze welding is perhaps the most common of the many terms in everyday use that refer to a particular type of brazing. It may be defined as the joining of hot, solid metals by the flowing of a high zinc bronze filler rod into an open vee or fillet at temperatures between 1600° and 1700°F. "Bronze welding" implies, through common usage, a joint design and a manner of employing the filler metal similar to that which would be in effect if a fusion weld were being made. However, it is felt that this term is not truly descriptive of the operation. Further, care must be exercised when it is used in referring to the joining of bronze base metals. The melting points of the filler rod and the base metal determine whether the process used is welding or brazing—whether the side walls of the base metal are melted or not.

For simplicity, we will refer to the process as "brazing" although in some

* Prepared by a committee consisting of R. N. Chapin, Air Reduction Sales Company, *Chairman;* J. F. Galbraith, The Linde Air Products Company; I. T. Hook, American Brass Company; E. W. P. Smith, The Lincoln Electric Co.; J. J. Vreeland, Chase Brass & Copper Co.

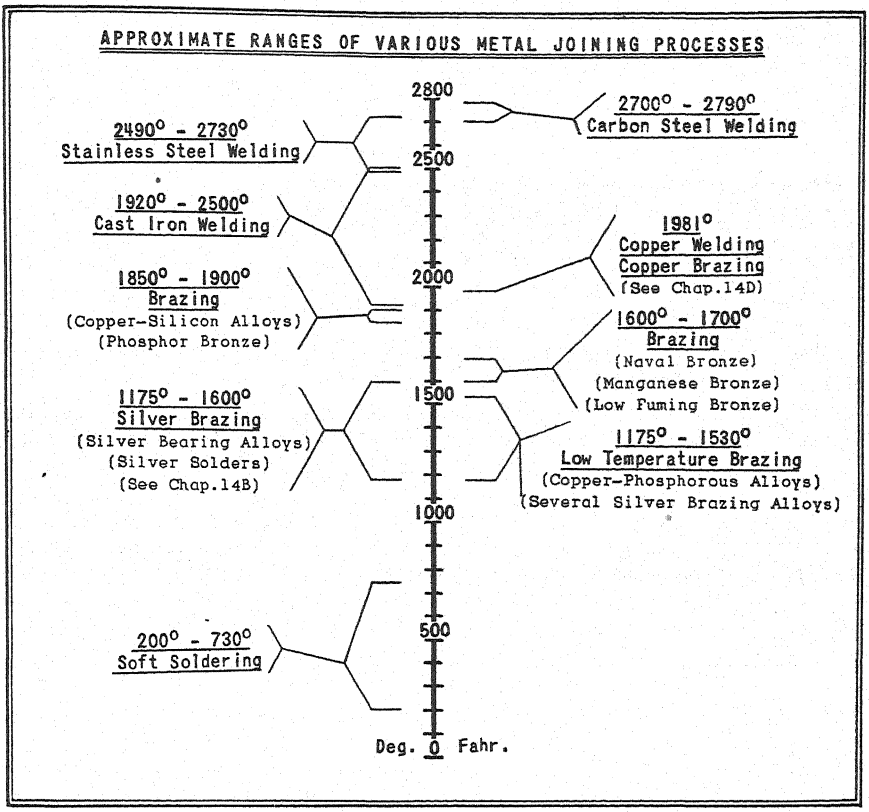


Fig. 1

cases the reader may recognize the procedure as that which he may know as "bronze welding."

Braze Welding.—This term seems to be an attempt to bring in the thought of brazing with a non-ferrous filler material and also convey the thought of strength inferred by use of the word "welding." It is synonymous with "brazing."

Low-Temperature Brazing.—A brazing process using various alloy compositions as filler material whose flowing points range from 1100 to 1600°F. Alloys most commonly used are copper-phosphorus and several of the lower melting point silver brazing alloys (silver solders) described in Chapter 14B.

Copper Brazing.—A brazing process using electrolytic copper in powder, wire or strip form as filler material to join steel, nickel, cupro-nickel or cast iron. Copper brazing is usually done in a reducing atmosphere and is often called copper hydrogen brazing or electric furnace brazing (see Chapter 14D).

Spelter Solder Brazing.—A brazing process in which spelter solder, com-

posed of 45 to 52% zinc and the remainder copper, is used as a film introduced at a temperature slightly above its melting point to bond lapped surfaces of the base metal. The solder is usually in granular form and the joint is of the scarf type in order to secure a joint length several times the thickness of the plate. Heating is accomplished by setting the parts to be joined on a charcoal bed or by gas heaters, bringing the whole mass of the parts up to the flowing temperature of the alloy—usually about 1615°F.

Metals That Can Be Brazed

The widespread usefulness of the brazing process is particularly evident when consideration is given to the vast range of metals that can be joined by this process. Below are listed some of those most often joined by brazing.

Cast Iron.—Brazing is particularly well adapted for joining cast-iron parts. As it does not require melting of the base metal, the considerations which are necessary to insure the proper gray iron structure in a fusion weld are, for the most part, eliminated. Because of the lower temperature required, preheating is greatly simplified. In many cases, the requirement for local preheating makes it possible to repair broken machines in place, thus saving the time and expense of dismantling and assembly.

Malleable Iron.—Brazing is the usual method of repairing malleable iron. Because of the relatively low temperature at which the bronze is applied, the malleable properties of the material are not seriously affected as would be the case with fusion welding.

Carbon Steels, Alloy Steels and Wrought Iron.—The brazing of low carbon, medium carbon and high carbon steels and wrought iron is an application of the brazing process that is widely used and also offers many possibilities. With the all-purpose bronze rod, joint strengths of 55,000 to 60,000 psi. can be obtained easily. Practically any of the various alloy steels can be satisfactorily brazed since the low heat of application is not sufficient to materially affect the normal properties of the alloy. Brazing should not be used for any parts that require heat treatment after joining as the heat treatment may melt the brazing material.

Galvanized Iron or Steel.—Brazing is a highly useful method for joining galvanized iron or steel because the galvanized coating is not seriously affected. In making a bronze joint on galvanized parts, the surfaces forming the vee are always kept well below the fusion temperature with the result that the heat has only a localized effect on a narrow strip of the zinc coating. The liquid fluxes developed in recent years have proved to be paricularly well suited for this work when applied on the galvanizing of alt the edges of the joint. They form a protective coating that minimizesl the oxidation of the thin layer of zinc. Should the zinc be removed from the abutting ends for a short distance, perhaps $1/8$ in. or $1/16$ in. on the surfaces adjacent to the joint, in many instances a thin film of bronze may be easily spread along this area much as solder spreads on a properly tinned surface where the heat is right. Experience has shown that brazed joints on galvanized material are fully as corrosion resistant as the rest of the material under most service conditions.

Copper.—A popular method of joining copper is by brazing. It is

generally recommended that this process be used except in cases where an absolute color match is desired, or where the bronze filler metal will not meet certain service requirements, such as corrosion resistance.

Brass and Bronze.—Brazing is widely used for joining brasses, bronzes and other copper base alloys that have a melting point higher than that of the bronze rod being used.

Nickel, Monel and Inconel.—Silver brazing alloys with a low flowing temperature are recommended for joining high nickel materials. Monel is subject to intergranular attack by molten brazing alloys and failure, if under even low stress at temperatures of 1400°F. or higher. In general, lap joint design is necessary to develop full strength. Phosphorus-bearing alloys must not be used on these materials because of the embrittling effect of this element.

Dissimilar Metals.—The fact that molten bronze will flow onto the clean heated surface of a higher melting point metal to give a strong bond makes the brazing process ideally suited for the joining of dissimilar metals, such as malleable iron or copper to iron or steel.

Limits of the Brazing Process.—In general it may be said that the metal or alloy to be brazed must have a melting point at least 100°F. higher than the brazing alloy being used. In addition to this qualification, there are some metals that cannot be brazed because of the oxide condition that exists when they are heated.

Brazing Materials

High Zinc Bronzes.—Probably the first brazing rods used were 60% copper and 40% zinc. This produced the best combination of high-tensile strength and ductility. However, there are other factors equally important that must be considered:

(*a*) The rod must tin the base metal readily when used with a suitable flux.

(*b*) It should be capable of building up deposited metal that is practically free from defects such as slag inclusions or blow-holes.

(*c*) It is desirable that fumes from the zinc or other ingredients be kept at a minimum.

Inasmuch as joint strengths depend so greatly on the filler metal, the quality of the brazing rod and flux that are used is of great importance. Recent years have seen a number of developments of the rods used for brazing. Several types of filler rods are now in general use which have varying compositions of a proprietary nature. They have been designed to incorporate the desirable qualities mentioned above and are marketed by the leading suppliers of these materials.

One of the most popular bronze rods in use today is an all-purpose rod which contains a few hundredths per cent of silicon, in addition to the alloying elements of zinc, tin, manganese and iron. The silicon performs several important functions that are of value to the brazing operation and makes silicon-bearing rods distinctly different from other brazing rods. This element functions as a deoxidizer that removes oxides of tin, copper and zinc and replaces them with silicon dioxide which floats readily to the

surface of the molten puddle to combine with the usual brazing fluxes. A further function of the silicon is to aid in forming a protective film over the puddle which greatly retards the fuming and oxidation of the relatively low melting point zinc and keeps the heating gases from contact with the fused metal. The result is that the deposited metal is dense and free from porosity or blow-holes, thus increasing the strength and improving machinability. The all-purpose brazing rod containing silicon will consistently give joints in the usual grade of steel tank plate with a strength of over 55,000 psi., and in many cases joint strength has exceeded 60,000 psi. The ductility of metal deposited from this rod is in excess of 30% in 1 in. on all-weld-metal specimen.

Also, because of the carefully balanced content of deoxidizing and reducing agents, this rod is remarkably free flowing and lends itself very readily to sectional building up of large deposits, where successive layers are added one after the other.

Silicon Bronze and Phosphor Bronze Rods.—These two alloys are being used in increasing quantities in the brazing of steel using the carbon arc method. This is a natural development following the wide application of the carbon arc for the welding of bronzes and copper. The joining of galvanized iron and steel with little disturbance of the galvanizing is a practical application with these rods using the carbon arc.

Low-Temperature Brazing Alloys.—Brazing alloys that flow at the relatively low temperatures of 1175 to 1530°F. are becoming increasingly popular. Some of those most commonly used are the copper phosphorus and two of the silver brazing alloys having silver percentages of 15% and 50%.

Copper.—Pure copper wire has given excellent results in the brazing of ferrous parts. In some cases, heating is accomplished with the oxyacetylene torch, but the majority of this type of work is done in a furnace. For further details see Chapter 14D.

A few of the more commonly used brazing alloys are described above. Where unusual conditions exist and special rods or form of alloy seem advisable, it is suggested that the rod manufacturers or welding supply companies be consulted.

Table 1 shows the percentage ranges of the brazing alloys used most often in industry today.

Fluxes

Action.—Fluxing is a vitally important operation that only too often is not properly understood. Many operators use flux because instructions indicate that this must be done. Many reported troubles with brazed joints can be traced to improper fluxing practice.

In view of the fact that most of the brazing operations are carried on in an uncontrolled atmosphere, a flux is necessary so that these fundamental conditions are cared for:

1. To protect the base metal and filler rod from oxidation in the heating stage.
2. To dissolve any oxides that may be formed on the base metal or bronze rod during the period that the rod is flowing.

Table 1—Brazing Alloys and Their Composition, Form, Flow Point and Approximate Uses

Group No.	Inclusive Composition, %	Approximate Flow Point, °F.	Appropriate Uses, Remarks
1.	*Phosphorus-copper alloys* in cast or hot-rolled rod or strip form		
	4 to 8 Phosphorus 0 to 1 Tin Remainder copper	1300–1530	Self fluxing on copper. Recommended for sweat brazing overlapping surfaces of copper or copper alloys. Not recommended for steel or cast iron. Torch brazing, dip brazing, furnace brazing
2.	*Silver brazing alloys*, silver solders in strip, sheet, wire or, less frequently, in powder form. Given here for sake of completeness. See Chapter 14B		
	0 to 8 Phosphorus 5 to 80 Silver 0 to 25 Zinc 0 to 18 Cadmium Remainder copper	1175–1600	For sweat brazing of overlapping surfaces of copper alloys, nickel alloys, ferrous alloys. Brazing alloys containing phosphorus not recommended for steel, cast iron or other ferrous alloys. Torch brazing, dip brazing, furnace brazing
3.	*Spelter brazing alloys* in powder, lump or molten bath form. Golden yellow without nickel, white with 10% nickel		
	45 to 55 Zinc 0 to 10 Nickel Remainder copper	1550–1650	For sweat brazing copper alloys, nickel alloys, cast iron and steel. Dip brazing, torch brazing, furnace brazing
4.	*Brazing metal, Muntz metal.* 60:40 brass rods for inexpensive, moderate strength brazed connections		
	38 to 42 Zinc Remainder copper	1625	For sweat brazing of copper alloys, nickel alloys, cast iron and steel-making joints of only moderate strength and soundness. Not recommended for open vee or fillet connections. Torch brazing, furnace brazing
5.	*High zinc yellow* (white with 10% nickel) *brass and bronze welding rods* for general purposes in open vee, fillet or sweat brazed connections yielding high-strength, sound joints		
	0 to 0.50 Manganese 0 to 1.50 Tin 0 to 1.50 Iron 0 to 10 Nickel 0 to 0.15 Silicon 38 to 42 Zinc Remainder copper	1600–1650	Applicable with oxyacetylene torch to copper alloys, nickel alloys, cast iron and steel. Joins dissimilar metals. Makes excellent wear-resisting surfaces. Not recommended for arc welding
6.	*Silicon bronze or phosphor bronze* for carbon or metallic arc brazing of copper and steel		
	0 to 4 Silicon 0 to 1.25 Manganese 0 to 10.5 Tin 0 to 2 Zinc 0 to 1.5 Iron 0 to 0.5 Phosphorus Remainder copper	1850–1980	Applied most frequently by the carbon arc in brazing thin bare and galvanized sheet steel, in making wear-resisting surfaces and in joining copper to steel. See Chapter 15B on Bronze Surfacing
7.	*Pure Copper* See Chapter 14D for complete details	1981	Generally used on ferrous parts in a furnace having a reducing atmosphere

3. To keep the finished joint and surfaces of the base metal adjacent thereto from oxidizing during the brazing and later on during the cooling process.

Added to these three basic functions there are two more requisites of a good flux under some conditions:

1. Special purpose constituents are used occasionally, as, for example, an oxidizing constituent to aid in the elimination of graphite interference in the brazing of cast iron.
2. Film-forming constituents are added to reduce the vaporization of zinc, primarily in the brazing rod but occasionally when brazing on galvanized material.

Almost all of the elements present in both the filler rod and the base metal will oxidize in varying degrees when heated to the temperature necessary for brazing. The action of these oxides are not all the same but they all will interfere to some degree with the proper alloying of the bronze filler rod and the base metal.

The mechanism of the fluxing action is not always well understood. In cases where the oxides are soluble in the hot liquid flux, the flux with the dissolved oxides is replaced with the heavier fused filler metal which appears to be attracted to the hot flux-cleaned base metal. The liquid brazing alloy will spread readily on these cleaned surfaces of base metal. It is important to remember that fluxes are not fully active and cannot dissolve metal oxides until they are hot enough to become completely molten or liquid. Most fluxes are made up largely of fused borax, sodium tetraborate ($Na_2B_4O_7$) and/or boric acid (H_3BO_3). Common mixtures of these constituents will melt at approximately 1350°F. When it is desired to keep the base metal from oxidizing in the heating stage, it is necessary to add a lower melting constituent such as zinc chloride or potassium acid fluoride. On the other hand, if higher melting temperatures are required as for brazing of aluminum bronze, beryllium copper and chrome iron and steels, other chlorides and fluorides melting at higher temperatures are used.

A special flux is sometimes used for "tinning" the surface of gray or malleable cast iron with the bronze after which the further deposition is done with the usual brazing flux. Potassium chlorate may be sprinkled liberally on the red-hot iron. It gives off oxygen which unites with the graphite on the surface to go off as a carbon gas leaving the iron exposed for the filler metal to surface alloy thereto. Manganese dioxide and, less frequently, iron oxide are sometimes used for the same purpose but in this case it is necessary to mix these two constituents with a borax base flux as otherwise the high zinc bronze will not "tin" the cast iron. After the cast-iron surface is given an initial coating of the filler metal, the joint may be completed with the usual brazing flux.

The oxides of copper, zinc, iron, silver, silicon or manganese rarely remain in the deposited metal while tin, cadmium or lead oxide may become entrapped if not properly fluxed.

Common borax that may be purchased in local grocery or drug stores is used as a flux in many of the smaller shops as it is less expensive than the prepared powdered brazing fluxes sold by welding supply companies. However, common borax "crawls" away from the heat

when giving up its water of crystallization and the metal surface it is intended to protect is exposed to oxidation. This action renders it largely ineffective.

Forms of Flux.—Fluxes, as originally applied to base metal surfaces and to the brazing rod or finely divided brazing alloy may be in the following forms:

(*a*) Powder.
(*b*) Paste or liquid.
(*c*) Vapor or gas.
(*d*) As a coating on the filler rod.

The powdered flux is frequently used. It becomes sticky at temperatures above 1000°F., and will, therefore, cling readily to the base metal or hot end of the brazing rod. The one objection to this form of flux is that it has a tendency to blow away in the initial blast of the torch flame thus exposing the bare metal.

To overcome this loss of powdered flux, it is often mixed with water or alcohol and painted on base metal and rod with a brush. There are now available several commercial brazing fluxes prepared in liquid or paste form. These may have a part of the fused borax replaced with boric acid which is more soluble in cold water than is the former. Also, such liquid fluxes may contain water-soluble chlorides or fluorides which usually melt at a lower temperature than borax or boric acid, thus providing additional protection in the heating stage. If these added constituents such as sodium chloride, zinc chloride and sodium or potassium fluoride or acid fluoride are used, they will aid materially in dissolving the recalcitrant oxides of aluminum, beryllium and chromium.

The vapor or gas flux is usually applied to the base metal and filler rod through the medium of the oxyacetylene flame. The acetylene or other fuel gas used is passed through the flux solution and picks up a small quantity that is burned in the flame, thus being deposited wherever the torch is directed. It should never be introduced through the oxygen hose. A fluxing constituent soluble in alcohol or methyl borate is sometimes used.

The flux-coated high zinc bronze filler rods are commercially available and are convenient to use. In some cases, it is necessary to flux the base metal with powdered or liquid flux as well, for the surfaces may become oxidized in the heating stage. Thus, the melted bronze from the flux-coated rod will flow onto some part of this area before the flux from the coating has had an opportunity to dissolve the oxide therefrom. The flux coating does, however, eliminate the necessity of frequent dippings of the hot rod into the flux can.

Procedures

Preparation of Joint.—For successful brazing, the surfaces must be properly prepared and free from oxides, dirt, oil and grease. It is advisable to bevel to a 90° included angle all edges $^{3}/_{16}$ in. and heavier. Grinding or machining are acceptable methods for the preparation of the edges of all materials except cast iron. Edges of cast-iron parts should be prepared by chipping. Grinding or machining tends to smear the graphitic carbon present. To eliminate the presence of graphite smear, the edges should first be quickly heated to a dull red with the torch.

A good brazing flux should be used throughout the process. It is advisable to coat the edges to be joined with a thin mixture of flux and water before preheating to give added protection against oxidation during the heating period.

Correct alignment of parts adds considerably to the success of the finished joint. This is usually accomplished by the use of jigs and fixtures (see Chapter 32C. The purpose of these jigs and fixtures is to minimize warpage and distortion, to locate parts and to hold them in position during the brazing operation and to facilitate the positioning of the work for the operator. Fixtures to control warpage and movement of metal are most frequently required for the brazing of thin sections ($^1/_8$ in. and thinner).

After complete alignment is accomplished, the joint and parts to be brazed should be properly preheated to minimize unequal expansion of the parts. The chill should be removed from a large area of metal surrounding the joint, before the joint is gradually brought up to proper brazing temperature. Occasionally a complicated part, made up of thin and heavy sections, should be completely preheated on a preheater before brazing. When this is done, it is also advisable to return the part to the preheater after brazing is completed to bring it nearly to the brazing temperature to permit uniform cooling and lessen the hazard of cracking.

Methods of Heating.—The oxyacetylene torch or blowpipe is the most common method of heating for brazing in industry for both repair and fabrication. A slightly oxidizing flame should be used to insure proper results yet a neutral flame would also yield satisfactory results. The torch tip size used should be one that minimizes the preheating time without causing melting of the edges to be joined during the brazing operation.

Furnace brazing is used quite extensively for mass production in the joining of small parts. Copper wire or powder and brass alloy brazing wires or thin strip are used as the brazing medium. Parts are held firmly together in fixtures, after the brazing medium and flux are placed in a position so designed for their use. See Chapter 14D for further details.

Dip brazing is a more recent development and is also used for mass production but not on quite as an extensive scale as furnace brazing. The assembly of the parts is identical with that for furnace brazing. The parts when assembled and held firmly by means of fixtures are immersed in a molten salt bath operating at a temperature sufficiently high to cause the brazing material to melt and flow. The choice of salt composition depends to a certain extent on the temperature required for satisfactory brazing.

Carbon arc brazing has found considerable application in industry because of the ability to braze at speeds approximately 20 in. per minute. By this method, one is able to join thin sheet steel and galvanized iron with a minimum amount of warpage and a minimum disturbance of galvanizing. With the proper set-up, using a removable chill bar or a "joggled" joint, and low-heat settings (30–60 amp., 13–18 v.) on the welding machine, fast efficient joining can be accomplished using either silicon bronze or phosphor bronze as filler material.

The carbon arc torch is also used for brazing but has only been found

practical for thin sheets ($^1/_{16}$ in. and under). This gets its name from an arc flame sent off from between two carbon electrodes so positioned that the flame is controlled as to direction. The high temperature of the flame makes it difficult to handle since the heat is not concentrated as with the carbon arc. It is used in much the same manner as an oxyacetylene torch.

Electric resistance brazing has been used for a great many years. However, it is only recently that its evident advantages have become widely appreciated. Two closely related methods are used depending upon the character of the work. The heat is generated by the passage of current of the order of thousands of amperes through the parts being brazed and through blocks of carbon immediately adjacent. In some cases, the heat is developed by the resistance of the work itself. In other cases, the carbon blocks develop the heat. The latter method is probably more widely used. As this type of brazing is used most extensively on the low-temperature copper phosphorus and silver brazing alloys, it is described in detail in Chapter 14B.

Physical Properties of Completed Joint

The advantage arising from the use of joints made with the high zinc bronze rods is that the residual stresses are as a rule quite low by reason of the plastic yielding of the bronze in the cooling stage. Such bronzes have appreciable amounts of beta brass constituent which is soft and ductile when hot. A large part of the contraction strain takes place before the cooling filler metal reaches 500°F., and is therefore absorbed by harmless plastic stretch in the bronze. The elastic limit and tensile strength of the filler metal then increase rapidly as the temperature drops to that of the surrounding air with not much change in ductility. Hence, the residual stresses are rather moderate and can do little damage in view of the high residual ductility.

Fusion butt welds made in $^3/_8$-in. thick manganese bronze plate with some of the higher strength high zinc bronze brazing rods will develop a normal strength of 56,000 psi. for the usual reduced section tensile specimen. These rods are usually strengthened with tin and iron. The high zinc bronze brazing rods without tin and iron will develop about 50,000 psi. in a weld on manganese bronze plate.

Like many experimental quirks, liquid flux was not developed with the thought of increasing tensile strengths. Original experiments were intended to prevent welding rods from fuming by changing the flux instead of the rod composition. Although this aim was attained, it seemed more important to emphasize the by-product of this accomplishment, namely, the improvement in the physical characteristics of the weld metal.

Density or lack of minute voids is a controlling factor affecting tensile strength, ductility and hardness. By obtaining a more solid deposit of the braze metal, these qualities have been increased upward of 20%. In brazing steel, the bond strength between the bronze filler metal and the steel, due to the protection afforded by the flux, has been increased to the point where unreinforced 90° vee butt joints tested in tension have failed in the steel base metal. The brazing operation has been speeded up and simplified and even the appearance of the joint has been improved. Fur-

ther applications of brazing, that were never before quite satisfactory, such as brazing red brass and galvanized pipe, are opening up due to the liquid flux.

Figure 2 shows carbon steel test coupons of 65,000 psi. brazed with liquid flux and manganese bronze rods of a composition that has been used for the past twenty years. The central specimen together with the face and root bend specimens were tested in the standard guided bend jig.

The normal deposited bronze metal will have an approximate Brinell hardness value of 100 (500-kg. load). This in itself is not the true criterion for a wear-resisting surface. A wear-resisting deposit should contain hard

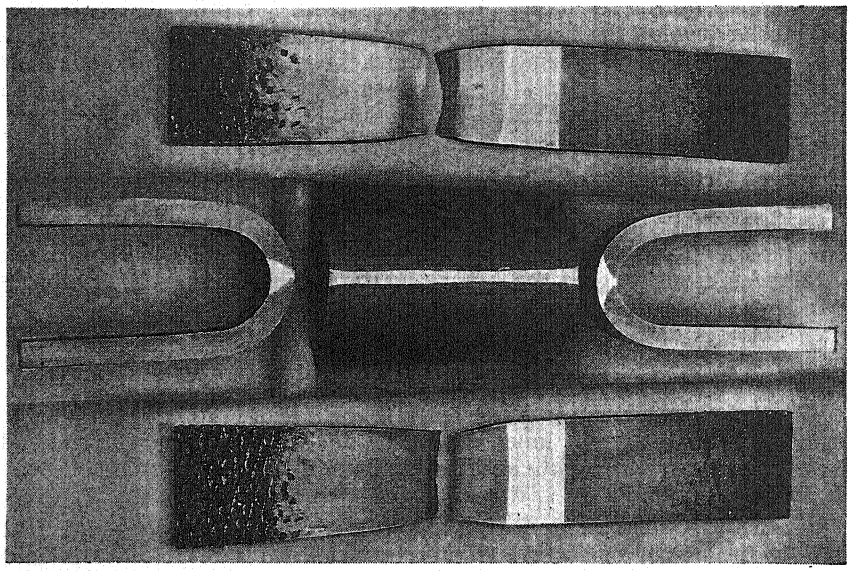


Fig. 2—Test Coupons of 65,000 Psi. Steel Plate Showing Joints Made with Manganese Bronze Rods and Liquid Flux

particles imbedded in a soft matrix. This is obtained in the bronze rods containing approximately 1% iron which permits the formation of a hard iron-rich constituent imbedded in the soft alpha matrix. High percentage of beta brass constituent which is also quite hard will also render a bronze capable of resisting wear.

It must be remembered that all these bronze rods are high zinc brass and are subject to dezincification failures. High acidity and high temperatures are ideal conditions for rapid failure due to this cause. If metals other than ferrous alloys are to be joined, consideration should be given to the service for which they are intended.

Applications

General.—The field of application for brazing is exceptionally broad. A particular process such as spelter brazing, dip brazing or low-temperature

brazing may be restricted to some extent in its use by inherent limitations, and some overlapping of the numerous brazing processes is to be expected; nevertheless so much can be accomplished by brazing that applications for it are to be found in practically all industries.

Its advantages are many: it can be applied to a wide variety of ferrous and non-ferrous metals and alloys; it gives a joint or a surface with highly desirable properties; it involves relatively low temperatures; it is simple to apply and therefore requires less highly skilled operators than welding; operations for which it is used can frequently be easily mechanized; and, largely because of all of these factors, it is very economical.

Brazing, however, is not aways the solution to a problem because it also possesses certain limitations. Thus, if the brazed part is to be exposed to corrosive media, some thought should be given to whether or not the filler metal has the required corrosion resistance. The temperature conditions under which the brazed article operates must also be investigated because of the low temperature at which most brazing alloys lose an appreciable part of their strength. A broken cast-iron part repaired by brazing cannot be used at as high a temperature as before the break occurred.

Another limitation is that of color. The filler metals used for brazing vary all the way from silver-white through the various shades of bronze to copper-red, but they seldom exactly match the color of the base metal. It is fortunate, therefore, that in the majority of cases a color match is not essential, either because the brazed part is ultimately painted, or for some other reason.

With these advantages and limitations in mind, the field of application for brazing can best be disclosed by citing a number of specific examples. For this purpose, it is convenient to divide brazing operations into three categories: Fabrication, Repair and Surfacing.

Fabrication.—Brazing is not simply a repair or maintenance tool—it is often ideally suited for the fabrication of a wide variety of articles. To such advantages as ease of application previously mentioned, there can be added for this type of work the fact that brazed joints require less finishing than, for example, fusion welds, and are easier to finish. When galvanized material is used, yet another factor favors a brazed joint and that is the fact that it can be made with little or no effect upon the corrosion resistance of the adjacent base metal.

Among the articles fabricated by brazing are such diverse objects as bicycles, display stands of all types, the framework for floats in a parade, sheet metal trays, tables, racks and special frames for hospitals, chicken brooders, ventilating ducts, culvert specials and beds. One manufacturer has produced over 100,000 brazed army cots for the government and another well-known firm uses the same process on its standard line of beds, springs and similar items. Bicycles are fabricated by both dip brazing and torch brazing; mine rails are being brazed to reduce maintenance and operation costs and brazing is the most common method of joining carbide cutting tips to tool shanks.

Copper welding rods are also widely used for the joining of ferrous materials, particularly steel sheets and thin wall tubing. It melts at a higher temperature than most other brazing materials but it tins readily to steel, and particularly when compared to bronze rods, has such advantages as

the fact that no flux is required and that on zinc fumes are released. These factors contribute additionally to the ease of cleaning and to the speed of fabrication. Copper welding rods are used on such parts as automobile tire pumps, children's cribs, washing machines and many others. A great deal of the copper brazing is done in furnaces wherein a reducing atmosphere is maintained.

Repair.—Broken parts of all shapes and sizes can be quickly and economically repaired by brazing. Castings—steel, iron, brass and bronze—are most often in need of such treatment and parts so repaired can be expected to give service equal to or better than that of the original parts. In the automotive field, the process is applied to cylinder blocks, which can often be brazed in place, to bumpers, bumper brackets, radiator castings, differential housings and to dozens of other parts. Railroads use it in the repair of engine frames, cylinders, cylinder heads, air compressor bodies, stoker hopper castings and many other parts both large and small. Similar lists can be compiled for most industries.

A particularly common application which may be found in almost any industry is the repair of a broken engine base or frame. What can be accomplished is well illustrated in a plant where the base of a large bulldozer, used to pierce shell stock, fractured, due to an overload. This casting was 5 ft. wide by 15 ft. long by 15 in. deep and weighed from 5000 to 6000 lb. The break occurred through two bearing pads, two I-sections, one with a 15-in. flange 4 in. thick, the other with a 6-in. flange 2 in. thick, and through a 15-in. web 2 in. thick. The casting was veed out, preheated with natural gas and compressed air and then brazed with 350 lb. of manganese bronze rod, about 1700 cu. ft. of oxygen and 1400 cu. ft. of acetylene.

Figure 3 shows the repairs made by brazing on a broken cast-iron housing on a 33-in. rolling mill. The cross-section of the members broken is 14 in. by 20 in. and approximately 400 lb. of brazing rod were used in each braze. As can be seen in the illustration, these repairs were made without dismantling the machine to any great extent.

Other widely used repair jobs making use of brazing are the replacement of broken gear teeth and the safe-ending of chisels. When gear teeth are partially or even completely broken out, it is entirely feasible to replace all of the missing material with metal deposited from a bronze rod. In the hands of a capable operator, this can be accomplished so as to require very little machining to shape the tooth to final dimensions. Chisels and similar tools, which are often rendered unserviceable when the striking ends mushroom and fracture, can easily be reclaimed and put in a safe condition.

To do this, the battered end is removed with a cutting blowpipe, a $^1/_8$-in. shoulder is then ground around the new end and this is filled with bronze. It is also advantageous to treat new chisels in a similar manner.

Surfacing.—In addition to its use for joining, brazing is extensively used for building up or surfacing operations. A surface obtained in this manner may be desirable for one or more of several reasons.

In some applications, the only reason for using this process is because it is the easiest and most economical method of reclaiming a worn part. Thus, when holes in ferrous materials become elliptical or oversize because of wear, they can be built up, or completely filled with bronze from a welding rod and then redrilled. When threads become worn or damaged, the

area can be surfaced with bronze and then rethreaded; pulleys, cams, sheaves and hundreds of other parts may be thus reclaimed. The ease with which the deposited metal may be machined contributes materially to the desirability of brazing for this work.

Bronze and other copper base alloys are also applied to wearing surfaces because their physical and mechanical properties make them excellent

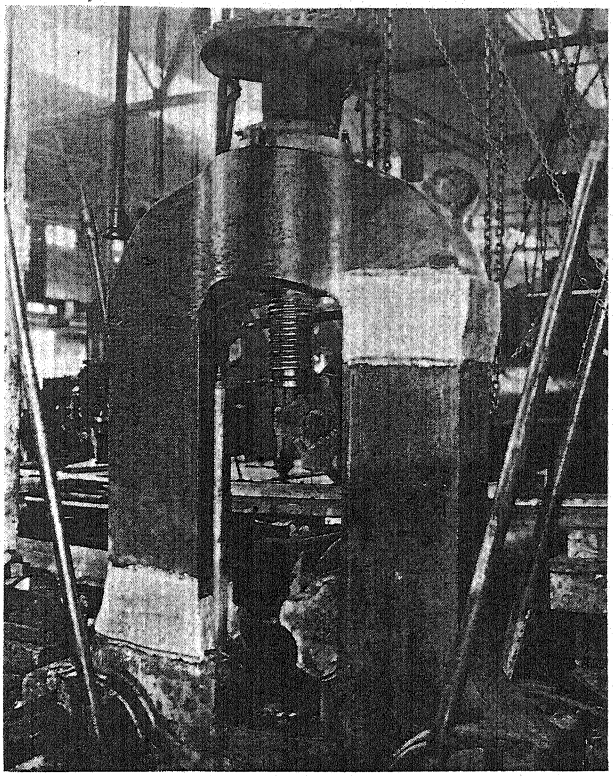


Fig. 3—Two Brazed Joints on 33-In. Rolling Mill Cast-Iron Housing

bearing materials. Wherever rotating or reciprocating parts are found, friction and wear are present, and the possibility of reclaiming worn parts or of providing an excellent bearing surface with bronze should be considered. One of the best examples of such work is the building up of pistons such as those found in compressors of all types, in locomotives and in other engines. One large gas company annually reclaims about 50 gas-engine power and compressor pistons at a saving of one-half the cost of new pistons. The same firm also salvages between 500 and 600 gate valves per year, by building up both the discs and the seats, for about one-eighth the cost of new valves.

Bearing areas on shafts and housings are also built up with bronze after

becoming worn in service. A typical example is provided by a paper manufacturer who had a cast-iron beater shaft 10 in. in diameter by 13 ft. long which had to be taken out of service because of wear at the packing gland. At this point, a band 5 in. wide had worn $^3/_4$ in. undersize. The shaft was mounted in a lathe, turned down somewhat to obtain a clean surface, preheated locally with a charcoal fire, built up with 35 lb. of bronze welding rod, turned to finished dimensions and then put back into service. See Chapter 15B on Bronze Surfacing.

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CHAPTER 14B

SILVER BRAZING ALLOYS* (SILVER SOLDERS)

Selection of Grade, Form, Design and Preparation of Joint, Assembling, Fluxes, Heating, Important Points When Using Silver Brazing Alloys, Bibliography.

SILVER brazing alloys include those alloys which for many years have been called silver solders. Although the term hard solder could be used to distinguish these alloys from the ordinary soft solders there is practically complete agreement on the part of producers and users that it is more appropriate to classify them as brazing alloys and thus eliminate any possible confusion with tin-lead solders and similar alloys.

Silver, copper and zinc are the principal components of the standard silver brazing alloys but other metals such as cadmium, tin, manganese and nickel are used. Their melting points will run from approximately 1175 to 1600°F., depending upon the composition, and it is this low melting range as compared with that of brazing alloys which has been an important factor in their wide industrial application. Silver alloys which have melting points above and below these temperatures are available for special conditions, but they are not used extensively.

Silver brazing alloys are free flowing, corrosion resistant and produce strong joints that withstand severe shocks and vibration. They can be used for joining practically all ferrous and non-ferrous metals and alloys except those having lower melting points, such as aluminum and zinc alloys.

It is evident that a large number of different compositions can be made by combining silver with one or more base metals, but Table 1 gives the compositions and some of the physical properties of a representative list of this type of brazing alloy.

SELECTION OF GRADE

The selection of the most satisfactory grade of silver brazing alloy depends upon different factors, such as composition and melting points of metals to be joined, temperatures and stresses and corrosion conditions

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that the joints will be subjected to in use. The lower grade silver brazing alloys are less expensive, but this factor should not be given too much consideration when making a choice. Properly fitted joints require only a small amount of silver brazing alloy and in many cases the shorter time required for heating and the safety factor against damaging the parts which are being joined will more than offset the greater cost of the higher grade alloys. Following is a brief description of the silver brazing alloys given in Table 1.

Table 1—Composition and Physical Properties

Grade	Chemical Composition, % Ag	Cu	Zn	Cd	P	Melting Point, °F.	Flow Point, °F.	Specific Gravity As Cast	Electrical Conductivity Cu = 100%
1	10	52	38	..	..	1510	1600	8.55	20.5*
2	20	45	30	5	..	1430	1500	8.80	24.4*
3	30	38	32	..	..	1370	1410	8.86	...
4	40	36	24	..	..	1330	1445	9.11	...
5	45	30	25	..	..	1250	1370	9.15	...*
6	50	34	16	..	..	1280	1425	9.37	24.4*
7	60	25	15	..	..	1260	1325	9.52	...
8	70	20	10	..	..	1335	1390	9.76	26.7*
9	72	28	..	..	..	1435	1435	9.95	77.1
10	80	16	4	..	..	1360	1460	10.05	46*
11	15	80	..	..	5	1190	1300	8.45	14†
12	50	15.5	16.5	18.0	..	1160	1175	9.49	23.9†

* Standard specifications Silver Brazing Alloys—A.S.T.M.
† Proprietary alloys.

Grade 1.—Although silver brazing alloys containing as low as 5% silver are used in limited amounts this alloy which contains 10% silver is about the lowest grade silver-copper-zinc alloy that it is practicable to use for brazing purposes. It can be used for joining iron and steel and any non-ferrous metals that will not be melted or damaged by heating to 1600°F. The alloy has high strength, malleability and ductility and the cost is low. Its use is also indicated in those cases where subsequent heat treatment of the joined sections at relatively high temperatures is required.

Grade 2.—The melting point of this alloy is sufficiently low to allow its use with extruded brass. It flows freely at temperatures above 1500°F. and makes strong joints with copper, copper base alloys, nickel silver, steel and iron.

Grade 3.—The increase of silver to 30% brings the flow point of this alloy down to 1410°F. It can be used with the same metals as Grades 1 and 2, with the advantage of having less tendency to damage parts from overheating.

Grades 4, 5 and 6.—Silver is in excess of either copper or zinc and the alloys are nearly white in color. These alloys and others varying slightly in compositions are the typical silver brazing alloys which have been used for many years. They can be used with steel, iron, copper, copper base alloys and nickel silver. They are malleable and ductile, flow freely, have good corrosion resistance and the strong joints made with them resist severe shocks and vibration.

For brazing Monel metal with silver brazing alloys it is advisable not

to heat above 1400°F. and Grade 5 which flows at 1370°F. can be used if care is taken.

Grade 6.—This alloy which contains only 16% zinc is one of the most popular grades and both this grade and Grade 5 have given excellent results for joining band saws.

Grade 7.—Flowing at 1325°F., this alloy is used for making joints on small parts and on alloys where higher temperatures would cause excessive grain growth or produce other undesirable effects. It offers a wider factor of safety with Monel metal than Grade 5 and is practically white (like silver) in color.

Grade 8.—This is a "white" alloy which is used by silversmiths and to a limited extent where either its ductility or corrosion resistance has shown its advantage over lower grade alloys.

Grade 9.—This grade is the silver-copper eutectic and has no melting range. It has a tendency to oxidize readily unless well protected with flux and is used to resist corrosive conditions where an alloy containing zinc or cadmium is not suitable.

Grade 10.—This is an extremely ductile and malleable white alloy. It has been found particularly satisfactory for joining copper rods which are subsequently drawn into fine wire.

Grade 11.—This is an alloy having a comparatively low flow point and is suitable for joining copper and copper base alloys. The phosphorus makes the alloy self-fluxing to a great degree. It should not be used with iron or steel. Tests have shown that satisfactory joints can be made with alloys containing 70% copper and 30% nickel, but its use is not recommended with Monel metal, nickel or nickel alloys in which nickel is the major constituent. The use of this grade has increased extensively in recent years for joining copper and brass pipes and fittings and also in the electrical field for the many different types of copper joints. It is a proprietary alloy which is sold under the trade name "Sil-Fos."

Grade 12.—The low flow point of this alloy combined with the strength of joints which can be obtained with steel, stainless steel, iron, copper, copper base alloys, nickel and nickel alloys makes it suitable for a wide number of industrial applications. It flows freely at 1175°F. and is highly resistant to corrosion. The use of this alloy has been particularly successful with Monel metal (see Chapter 24, Section I) and many other applications where its free-flowing property at 1175°F. gives it a marked advantage over other silver brazing alloys. It is a proprietary alloy sold under the trade name "Easy-Flo."

FORM OF ALLOY

Sheet

Because of their malleability, silver brazing alloys can be obtained in sheets in all gages down to a few thousandths of an inch in thickness.

The insertion of a sheet from 0.003 to 0.010 in. thick into the joint gives good results when making lap or scarf joints. The sheet of alloy inserted should be large enough to provide a thickness of alloy from 0.002 to 0.003

in. over the full area of contact of the pieces to be joined. When inserts of these thin sheets are used the parts should be jigged so that a light, uniform pressure can be applied to insure good contact between the surfaces of the joint when the alloy melts. Washers can be made from these thin sheets and used as inserts or joining flanges or spuds to tanks.

Strip

Silver brazing alloys in the form of rectangular strips of various widths and gages can be used for feeding into joints. When tubular members and fittings are to be joined, rings can be made from the strip and inserted into grooves cut in the fittings, before assembling and heating. These

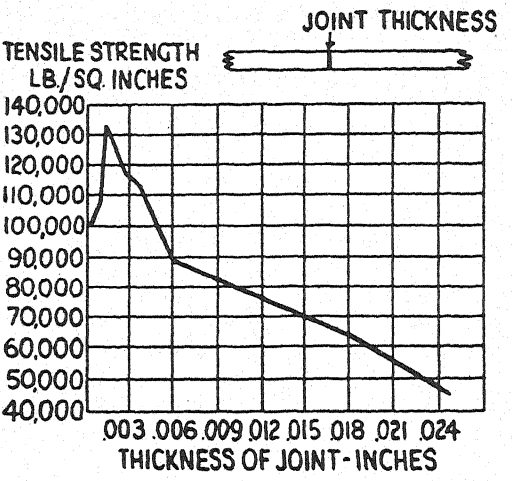


Fig. 1—Relation of Joint Thickness to Tensile Strength Based Upon Butt Joints of Stainless Steel to Stainless Steel with Grade 12 Silver Brazing Alloy

ring inserts must be large enough to provide sufficient alloy to completely fill the joint and allow a small excess. For outside feeding, care should be taken to select a size of strip in such proportion to the size of the joint that an excess length of strip will not be required. On the other hand, a strip having too large cross section will take a longer time to melt than one of the correct size.

Wire

Silver brazing alloys in wire form are most convenient and satisfactory for feeding into a joint from the outside, particularly when the heating is done by torches. The ductility of silver brazing alloys allows the drawing of wires down to small diameters for use in joining small delicate parts requiring very little alloy. Round, square and rectangular wire can be formed into rings for inserts. The same care in the selection of the proper size must be given as in the case of strip.

Filed, Powdered or Granulated Form

Silver brazing alloys can be obtained in filed form in sizes from 20- to 150-mesh. They are useful in those cases where it is more convenient to sprinkle the alloy along the joint before heating. There is a comparatively large surface of the brazing alloy exposed to oxidation, but with careful attention to protecting the alloy with flux these forms melt quickly and give good results.

DESIGN AND PREPARATION OF JOINT

Practically all types of joints can be made with silver brazing alloys but in order to obtain the best results it is necessary to recognize that these free-flowing alloys will penetrate into narrow openings and that small clearances will produce the strongest joints. The importance of the relationship between joint clearance and strength is illustrated in Fig. 1.

The alloy wire (Grade 12, Table 1) used in making these tests had a tensile strength of approximately 65,000 psi. and the 18–8 stainless steel had a tensile strength of 160,000 psi.

Design

There are three principal types of joints used in silver brazing: butt, scarf, and lap or shear, and each of them may be used with flat, round or tubular members.

Butt joints can be made that have remarkably high strength if proper care is taken in fitting and the members are held in close alignment during the brazing operation. They are useful in those cases where the double thickness of lap or shear joints is objectionable. One important use is in the production of hollowware articles which are made by stamping half sections from sheet metal and joining them. The edges must be cut or machined square and straight in order that a space of uniform width can be maintained between the members and they should be held closely together to insure even flowing of the alloy by capillary action.

Scarf joints are a modified form of butt joints and provide a greater bonding area for the same thickness of sheet metal. Joining band saws is a typical use of this type of joint and silver brazing alloys are used extensively for this purpose.

Lap or shear joints have the advantage of providing a bonding area the length of which can be varied by changing the length of the lap. The higher factor of safety against failure from breakage or leakage makes this type of joint more satisfactory when the joints must be leak-proof or are likely to be subjected to heavy stresses. Moreover, lap joints give a better opportunity to support the members properly and maintain correct clearances. Lap joints also allow a light pressure to be applied when joining flat sheets and if inserts of the brazing alloy are preplaced in the joint, the application of this pressure during heating will assist materially in producing an excellent bond.

The length of shear to be recommended will vary with different applications. Repeated tests have shown that when joining flat sheets of such

metals as copper, brass or Everdur, a length of lap approximating the thickness of the sheet will produce a joint stronger than the metal joined. Such tests, however, were made under ideal conditions where a light pressure was applied. In the case of tubular members, pressure cannot be applied, ordinarily, and many joints are made on flat sheets of Monel, steel and alloys having much higher tensile strength than those mentioned. Furthermore, the amount of alloying that will occur between the brazing alloy and the members will depend upon the composition of both as well as the time and temperature of the brazing operation. The amount of unchanged brazing alloy left in the form of a thin casting in the joint will depend upon the degree of alloying and the clearance in the joint. When tubular members or rounds are inserted in fittings or headers the percentage of the shear areas that are firmly bonded with the brazing alloy will show considerable variance. The tensile strength of silver brazing alloys will run from 45,000 to 60,000 psi. depending upon composition. Again referring to Fig. 1 we see that with a clearance of 0.009 in., which is more than recommended, the tensile strength of joint was greater than that of the alloy used. When all these factors are considered it is evident that it would be very difficult to attempt to give a precise formula for determining the length of shear or lap. Fortunately, however, silver brazed joints have such great strength that ample factors of safety can be provided and still keep the length of lap within the limits of good and economical design.

The following simple formula can be used with safety for determining length of lap or depth of shear on either tubular or flats.

X = length or depth of shear
T = tensile strength of weakest member
W = thickness of weakest member
Y = factor of safety
L = shear strength of silver brazing alloy

then $X = \dfrac{YTW}{L}$

Assuming 50,000 psi. as the strength of the brazing alloy and a factor of safety of 10 for tubular and 8 for flats we have the following examples:

Example I: Copper tube with 0.064 in. wall thickness in pipe fitting. Assume copper tube the weakest member and 33,000 psi. tensile strength of copper then:

$$X = \frac{10 \times 33{,}000 \times 0.064}{50{,}000} = 0.423$$

Example II: Lap joint on Monel metal sheet 0.050 in. thick. Assume tensile strength Monel 70,000 psi.

$$X = \frac{8 \times 70{,}000 \times 0.050}{50{,}000} = 0.56$$

A more accurate formula for tubular joints takes into consideration the shear diameter and wall thickness and the formula then becomes:

$$X = \frac{W(D - W)YT}{LD}$$

D = Shear diameter

and using values in Example I and D = 0.75 in. then:

$$X = \frac{0.064 \times (0.75 - 0.064) \times 10 \times 33{,}000}{50{,}000 \times 0.75} = 0.386$$

The difference in shear depth when this latter formula is used is so small with standard pipe or tubing that unless the wall thickness is unusually large the simple formula given first will meet all practical applications for silver alloy brazing of both tubular and flat sections.

The following comments refer to the illustrations in Fig. 2, which show good and poor designs for joints that are to be made with silver brazing alloys.

A—This is a typical V joint that is used when making butt joints with base metal alloys or welding rods. It is a poor design for silver brazing alloys and should never be used because it is wasteful of the brazing alloy and lacks the strength of a joint with small clearance.

B—This is the correct method of making a joint with silver brazing alloys. The edges should be square and straight.

C—The lap joint is a most satisfactory type. This design allows the use of inserts of the brazing alloy before heating although feeding may be done from the outside after the joint has been brought to the proper temperature. When inserts are used the members can be clamped together and the pressure exerted by the clamps will assist in making a good bond when the alloy melts.

D—The scarf joint also allows the use of inserts of the brazing alloy and this method is used in joining band saws and for those joints where double thickness of the lap joint is undesirable and greater bonding area than possible with a butt joint is necessary. Copper rods that are to be drawn into fine wire are joined in this manner.

E—This design is not good because the joint only has a bonding area proportional to the thickness of the metal. Heavy fillets on each side will increase the strength but they are wasteful of the alloy compared with the added strength obtained and are not recommended. It can be used, however, if for any reason it is not considered advisable to provide a lap on one of the members as shown in *F* and the joint will have strength comparable to base metal brazing alloys which require a much higher temperature.

F and *G*—These joints have the advantages common to all lap or shear joints and are recommended.

H and *I*—The design of *H* is preferred to *I* for several reasons. The lengthened hub on the flange makes the heating easier and more effective because only a small portion of the fitting has to be heated and the depth of shear can be controlled. The use of a preplaced insert in the groove shown in the fitting at *a* regulates the amount of brazing alloy used, and a proprietary method of making joints of this design has been adopted by several large manufacturers of fittings.

The brazing alloy can also be fed from the outside.

J—This illustrates a method of attaching spuds to tanks or any similar application. By preplacing a washer of the brazing alloy at *a* the members can be clamped together during heating.

K and *L*—The joint shown at *L* is another application of the lap or shear type that is much superior to joint *K*.

When a lock seam joint is made a thin insert of the brazing alloy can be preplaced between the members before the seam is locked. This method provides a very strong leak-tight joint.

Clearance

Modifications of the designs shown in Fig. 2 can be made but in all cases it is most desirable to provide clearances that do not exceed a few thou-

sandths of an inch. In making pipe joints, particularly in the larger diameters, clearances of 0.008 to 0.010 in. may be necessary because of the difficulty of maintaining pipe diameters to closer tolerances, but where better tolerances can be maintained a clearance of 0.002 to 0.003 in. is preferable.

Drive fits should not be used.

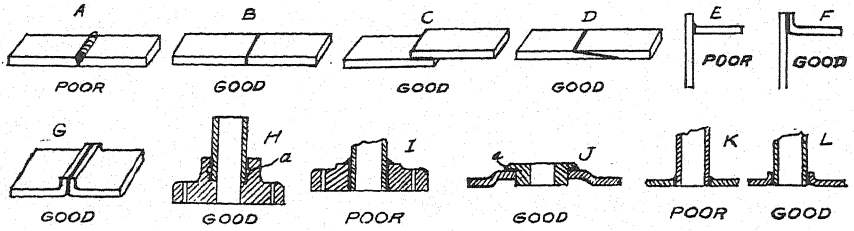


Fig. 2—Designs of Good and Poor Joints for Silver Brazing Alloys

Cleaning

One of the most important factors in getting good joints is to have the surfaces free from grease, oxide, scale and dirt of any kind. There are two methods usually employed: chemical and mechanical. Degreasing as well as the removal of oxides or scale by acids should be classed under chemical. Don't try to clean the grease off by burning; use one of the many reliable chemicals that are available such as trichlorethylene, trisodium phosphate and others. If the oxide or scale is removed by acid dips be sure to rinse well and dry; if this is not done any residual acid will attack the surface and form an undesirable film.

Mechanical cleaning is often the most convenient and satisfactory. First wipe off all the grease with a piece of clean waste or cloth and then remove any scale or oxide with a piece of fine emery cloth. If a file is used it should be a fine cut, as deep file marks may cause trouble. Grinding with a fine wheel provides a very satisfactory surface.

Careful attention to thorough cleaning is necessary if the best results are to be obtained and the cost of this operation is justified whenever silver brazing alloys are used.

ASSEMBLING

Fluxing

After the joints have been fitted and properly cleaned, brush an even coating of flux over the surfaces being joined. Avoid bare spots because they will oxidize at temperatures below that at which the flux becomes fluid. More detail regarding type of flux and methods of use is given in subsequent paragraphs.

Jigging

Suitable clamps and supports should be provided to hold the parts securely in position during heating. The design and size of the clamps or supports will depend upon the size, shape of the parts, and type of joint.

When thin inserts of silver brazing alloys are used, pressure is needed to insure that surfaces of the parts are brought together when the alloy is liquid. Contraction and expansion with the accompanying distortion and warping must be controlled.

The design of the jig or support will also depend upon the method of heating. When the whole assembly is to be placed in a furnace, consideration must be taken of the fact that the clamps and supports will be heated to the soldering temperature and will expand accordingly.

Spot welding at points along the joint is a satisfactory method of holding thin sheets and small stamped parts together. Consideration must be given, however, to the fact that these welds will interfere with the capillary action in the flowing of the brazing alloy if the weld completely closes the cross section of the joint and the brazing alloy must be applied on both sides of the welds.

If the heating is done by a torch, care must be taken to support the parts so that the workman can apply the flame easily to all parts of the joints; otherwise the workman is tempted to excessively overheat the parts of the joints to which he can directly apply the flame in order to more quickly heat the part that depends upon the conductivity of the metal for heating to proper temperature.

Another important point is to be sure that the parts are held firmly in place until the silver brazing alloy is set. Do not move the assembled part in any way that would throw any strain on the joint until the brazing alloy is thoroughly solidified.

FLUXES

General Description

Fluxes are used to prevent oxidation of the alloy and surfaces of the metals being joined, to dissolve any oxides that might form during heating and to assist the flowing of the alloy. They should be fluid, chemically active and free from excessive fuming at the brazing temperature.

When the proper flux is used it is a good temperature indicator because the joint should be heated until the flux remains fluid if the torch flame is removed for an instant.

Chemical Composition

Common borax and mixtures of borax and boric acid have been used for many years as fluxes for silver brazing. Borax is fluid at 1400°F. but begins to thicken at temperatures below this point. The addition of boric acid tends to make a more viscous flux and it is not as active as borax in dissolving oxides of metals. Boric acid when heated does not bubble like common borax but spreads over the surface of the joint thus protecting it from oxidation. The bubbling of borax when heated is caused by driving off the water of crystallization, and by using fused borax this can be avoided. Water should not be used to make a paste of fused borax as it will rapidly cake, but alcohol is suitable.

With the extensive use of silver brazing alloys melting between 1175° and 1300°F. it became necessary to develop a flux that would be extremely fluid and chemically active at these lower temperatures. Although borax can be used down to 1325°F. when extreme care is taken, there is some likelihood of flux inclusions which prevent tight joints and the activity of borax in dissolving oxides is much reduced at these lower temperatures. To meet this requirement a special flux which is extremely fluid at temperatures above 1100°F. was developed and has been used extensively with silver brazing alloys with great success. This type of flux contains fluorides and potassium salts and a proprietary flux of this type* is recommended for use with any silver brazing alloy melting below 1400°F.

Another flux which can be used with stainless steels is composed of one part of borax and one part boric acid made into a paste with a saturated zinc chloride solution. The zinc chloride should preferably be made by cutting zinc with hydrochloric acid until the acid is nearly spent and using this solution for making the paste.

Other halogen compounds in combination with borax and boric acid are also used but the fluoride types of flux are recommended when refractory oxides are likely to be present. For joining high aluminum bronzes or these bronzes to steel a special flux containing halogen compounds is recommended.

Form and Method of Using

The dry flux can be sprinkled along the joint but if a torch is used for heating it is advisable to warm the joint before applying the flux and this preliminary heating should be done sufficiently so that the flux will adhere and not be blown away with the torch flame. When filings of silver solder are used the flux can be mixed with them before applying along the joint.

A thin paste is a very satisfactory form because the flux can be brushed over the surface and an even coating applied. In brushing the flux, care should be taken to go back and forth over the surface to make sure that there are no bare spots.

When using borax as a flux a hot saturated solution brushed along the joint will leave a heavy coating of flux because of the comparatively large amount of borax which can be dissolved in boiling water. Better results are obtained if this hot saturated solution is brushed on the joint than when the pieces are dipped into the solution. Experience has shown that the application of an even coating of flux on all of the surfaces to be joined is very important and even clean pieces of metal will usually show bare spots if they are merely dipped into the solution.

Prepared fluxes are made by reliable companies in the form of powder, paste and solution, and can be purchased directly from the manufacturers or from supply houses or distributing agents. One should keep in mind that one of the advantages of silver brazing alloys is their low melting points and should select a flux that is fluid and active at the melting point of the alloy. This is particularly important in making gas-tight joints where flux inclusions might cause leakage.

* Handy Flux.

Fluidity alone, however, is not sufficient and the flux must be chemically active at the brazing temperature in order to insure that all oxide films are removed.

HEATING

Figure 3 gives a brazing process chart which gives the different methods that have been accepted by the AMERICAN WELDING SOCIETY. Any of these methods may be applied to the use of silver brazing alloys with the possible exception of the use of the electric arc. Because of the comparatively low melting point of silver brazing alloys the use of the electric arc should only be considered in some extreme cases where a welding rod of pure silver or a very high melting point alloy of silver is used and would therefore be classed more as a welding operation than brazing.

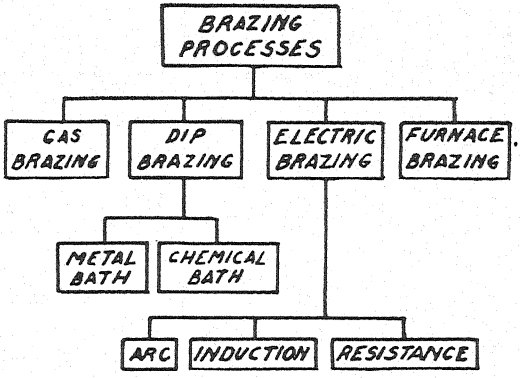


Fig. 3—Brazing Process Chart Adopted by American Welding Society

Torch Heating

Four types of torches are used for silver alloy brazing: air-gas, air-acetylene, oxygen-gas and oxyacetylene.

Air-gas torches give the least heat and when used on heavy parts the workman is inclined to use an oxidizing flame in order to hasten the heating. The air-acetylene type uses acetylene under pressure with air at atmospheric pressure and is available in suitable designs for use with silver brazing alloys, particularly those having lower melting points. Both the air-gas and air-acetylene torches can often be used to advantage on small parts and thin sections. Torches using oxygen combined with city gas, natural gas or any of the "bottled gases" such as butane or propane give a much hotter flame and when properly designed give excellent results

with silver brazing alloys. They should be of sufficient size to allow the use of a slightly reducing flame.

Oxyacetylene torches give a wide range of heat control and high temperatures are possible with a reducing flame. Manufacturers of these torches have developed them to a high degree of perfection and in the hands of a skilled workman they offer the most flexible and quickest method of heating. Their use is so universal that full information and instructions are readily available.

Specially designed torches having several tips can be used to advantage when a large number of units are produced. Care should be taken, however, to provide sufficient tips to prevent localized overheating in spots before the entire joint is at proper temperature.

When the brazing alloy is to be fed from the outside, heat the joint with the torch to a temperature above the melting point of the brazing alloy. Keep the flame in motion in order to heat as uniformly as possible. In order to obtain full advantage of the low melting temperatures of silver brazing alloys it is of course most desirable not to heat the joint beyond the temperature required for the free flowing and bonding of the brazing alloy. It is most important, therefore, that the term "let the heat in the joint flow the brazing alloy," is not misinterpreted by the workman. If he overheats the joint in order to be sure that he has a surplus of heat to melt the brazing alloy he will lose a great deal of the benefit of the low temperatures at which these alloys melt. The appearance of the flux and color are important guides to the workman in determining the proper heating of the joint. However, the varying light conditions may create some difficulties and another way the workman can obtain some guidance is by touching the brazing alloy wire or strip to the joint as the heating progresses. As soon as the temperature is high enough so that the alloy melts he can then take advantage of the heat from the torch flame by bringing the wire or strip under the torch flame momentarily. In other words, this technique is suggested in order that the attempt to make the joint itself a soldering iron will not cause overheating, but at the same time the joint should be at a temperature above the melting point of the brazing alloy and this procedure would be somewhat equivalent to feeding molten metal into the joint. Of course it is not desirable to play the torch flame for any considerable period of time on the brazing alloy.

The preheating required will depend upon the size, heat conductivity of the metals and type of joint, but be sure there is sufficient heat in the joint for the brazing alloy to flow freely or it will "ball up" and poor joints will occur. Poor work will often result if it is attempted to make the brazing alloy flow by applying more heat. The balling up tends to raise the brazing alloy above the film of protective flux and added heat only tends to oxidize the exposed brazing alloy. Furthermore, the higher temperature will tend to cause rapid diffusion of the brazing alloy into the members to be joined and in the case of thin sections this may be carried to such an extent that the workman speaks of "burning holes." What actually happens is that the diffusion of the alloy into the members leaves open spaces which have to be filled with more alloy. The correct way to repair a joint in which the brazing alloy has balled up is to allow it to cool sufficiently so that flux can be applied and then the reheating can be done carefully and the alloy properly flowed into the joint.

Furnaces

Standard types of heat-treating furnaces designed for muffle temperatures up to 1800°F. are suitable for silver brazing. As a rule it is better to run the furnace at a temperature well above the melting point of the alloy and thus heat the parts more quickly. The time in the furnace should be regulated so that the temperature of the parts only reaches the point necessary for proper flowing of the brazing alloy.

It is necessary to have the parts securely jigged with careful consideration of the effects of expansion and contraction.

Sealed furnaces containing hydrogen or some other non-oxidizing atmosphere are preferred but good work can be done in the ordinary muffle furnace if the joint is well protected with flux.

Reference is made to Section D, Chapter 14, for further and complete detailed information in regard to electric furnace brazing.

Salt Bath

A salt bath may be used for heating assemblies by placing inserts in the joint or on the outside of the joint before immersing in the molten bath. It is necessary that parts should be suitably jigged to hold them firmly together until the assembly has been removed from the bath and cooled to a point where the brazing alloy has solidified. Salt bath brazing has been increasing in use in recent years and is an effective medium for accurate temperature control when using silver brazing alloys. The correct application of this method of heating requires careful study for any particular class of work. It has been particularly successful where the brazing alloy can be applied in the joint and not directly exposed to the salt bath. When it is impossible to place the inserts in the joint and they are placed in the form of rings, for example, on the outside, dipping in molten salt may be arranged in such a way that the parts to be joined will be brought up to the brazing temperature during the immersion and the brazing alloy will then be immersed in the salt bath at practically the same moment that the parts themselves reach the proper temperature. This matter of technique of use of the salt bath is very necessary in order to obtain the best results.

Electric Resistance Brazing

The electric resistance brazing method has been developed to the extent that it can be applied to the brazing of joints of practically every description with respect to form and size. In principle, it consists in heating the joint members by heat conduction from hot electrodes. The electrodes are heated by current flow.

The hot electrode method has a number of important advantages:

It makes possible efficient and easily handled portable brazing equipment.

Stationary equipment is simple in construction, efficient in operation and durable.

Joint design is reduced to the simplest form; that is, flat sections lapped to non-critical dimension.

Joints are heated and cooled under pressure, insuring the strongest joints with minimum amounts of brazing alloy.

Temperatures of any required degree are readily obtained and easily controlled.

Joint members can be assembled and clamped securely in position by the apparatus which develops the heat.

Joints can be assembled with preplaced brazing alloy or the alloy may be applied when the joint arrives at brazing temperature.

Joints brazed by this method are invariably stronger than the adjacent section of the joint members.

This method is not limited to flat type joints as the electrode can be formed without difficulty to practically any contour.

The maximum voltage at the point of work is never above 12 volts, insuring no hazard to workmen.

The equipment for stationary set-up consists of: brazing transformer, press furnished with jaws to hold electrodes and means for the control of current to electrodes. The size of the various elements comprising the full equipment depends wholly on the maximum size joints that are required to be brazed.

The equipment for a portable set-up consists of: brazing transformer, devices usually known as "tongs" for holding and for conducting current to the electrodes which also serve as clamps for pressing the joint members together, cables to transformer and tongs and means for controlling current to electrodes.

The operation of brazing a joint, while requiring skill and experience, rarely becomes very difficult.

The joint is prepared by removing all heavy oxides, wax films and grease from the contacting surfaces. The surfaces should be flat for lap joints and all other type joints should be fairly well fitted.

The tongs are clamped to the joint members with enough pressure to insure good contact and prevent movement of members while being heated and cooled.

The alloy can be preplaced in the joint or may be applied when the joint arrives at brazing temperature.

Current is so controlled, usually by foot switch or special contactor, that the electrodes heat uniformly, avoiding "hot spots." The joint should be heated only to that state where the alloy is actively fluid. Additional heat is not necessary and may cause a weakening of the joint members closely adjacent to the joint.

The use of this method of applying silver brazing alloys allows full advantage to be taken of their low melting points because of the excellent control of the heating.

The electrodes commonly used are of carbon and can be obtained from any manufacturer of this material.

The rules previously given in respect to preparation and care of joints for any type of brazing apply to this method.

Another method of developing the required brazing temperature is by passing a current directly through the joint in which the silver brazing alloy has been preplaced. Although the low electrical resistance between the joint members makes very high current values necessary, equipment is available for making joints on copper and copper base alloys with silver brazing alloys which so limits the heat in the members of the joint as to prevent any coarsening of the grain structure beyond that produced at the minimum recrystallization temperature.

Induction Heating

This method has been used most successfully where inserts of the silver brazing alloy can be preplaced in the joint. The heating can be localized by proper design of the induction coil and the temperature control is excellent. Joints can be made very rapidly, a few seconds only being required in many cases.

Several companies are prepared to furnish high-frequency equipment suitable for this work, and where the joint is of a type that allows a coil to be placed around it, and a large number of units are to be made, this method deserves consideration.

Dip Brazing

Silver brazing can be done by dipping the parts into a bath of the molten alloy. This method is largely confined to joining small parts such as wires or narrow strips of metal. The parts should be clean and well protected with flux. The size of the bath will have to be such that there is no appreciable drop in temperature of the bath in the vicinity of the brazing operation. The ends of the wires or parts to be joined must be held firmly together as they are taken from the bath and until the alloy has thoroughly solidified.

IMPORTANT POINTS WHEN USING SILVER BRAZING ALLOYS

Select an alloy having a melting point well below the metals to be joined.

Have clean, well-fitted joints.

Use inserts of silver brazing alloy whenever possible.

Use a flux that is fluid and active at the flow point of the alloy.

Better results will be obtained if the alloy as well as the joint is protected with flux.

Apply the flux evenly, leaving no bare spots.

When inserts are used and the alloy and surfaces of the joint are not directly exposed to the flame or oxidation, use only a very thin coating of flux.

Provide suitable jigs and supports to hold the parts firmly in position to maintain proper clearance until the brazing alloy has set.

With thin sheet inserts a slight pressure should be applied.

Heat the joint evenly; where heavy and light sections are joined be sure that the heavy section is brought to the proper temperature.

When heating with a torch use a tip sufficiently large to give the necessary heat with a soft neutral or slightly reducing flame.

If joints are made on copper that has not been deoxidized, any appreciable excess of hydrogen in the torch flame or furnace atmosphere should be avoided because embrittlement of the copper will result.

Whenever possible avoid strong drafts and varying light conditions in the vicinity of the brazing operation.

As a general rule, the best results are obtained when the joint is heated rapidly and when kept at the brazing temperature for the minimum time required for proper flowing of the alloy.

Do not use any more heat than is necessary and remember that one of the principal advantages of silver brazing alloys is the low temperature at which they can be used.

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CHAPTER 14C

SOFT SOLDERS*

Composition of Solders, Available Forms, Soldering Action and Fluxing, Methods of Heating or Application, Strength of Joints.

SOFT solders are alloys applied at temperatures below 700°F. for joining metals such as: iron, steel, copper, brass, nickel, Monel, lead, tin and zinc. In general the solder alloys to some degree with the metals which it unites.

Available Forms

Pigs or ingots are bought for soldering baths, and pots of solder used when wiping. For general work the ordinary cast bar about 14 in. long by $^3/_4$ in. wide and $^1/_2$ in. high is used—it weighs about $1^1/_2$ lb. For soldering small parts, wire solder is frequently used. It can be obtained in great lengths and is most often $^1/_8$ in. diameter. It may be procured with a rosin core or core of other flux material. The flux generally weighs about 5% of the total. Small bars about $^3/_8$ in. square and triangular rods about $^3/_8$ in. on a side are popular forms. The wire or rod may be procured cut in short lengths which facilitate automatic soldering operations. Pulverized solder of 100 and 200 mesh is also marketed.

Soldering Action and Fluxing

The heat for melting applied solder may be furnished in several ways, but in all cases the molten solder functions properly only when it is in intimate contact with the parts to be joined. Generally these parts should be cleaned; sometimes pickling with caustic or acid solution, filing, sand blasting, scraping or other means are necessary prerequisites. Tinned metal is readily soldered. Occasionally it is necessary to precoat the parts to be soldered with solder (called tinning) individually, before assembling for final soldering.

Fluxing when soldering is necessary in all commercial work. Mild fluxes such as rosin and stearine principally tend to keep the parts made of copper or brass clean or free from oxide during the soldering operation while the solder is molten and the adjacent parts attain the temperature of

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Composition and Characteristics of Soft Solders

Tin, %	Lead, %	Antimony, %	Melting Range in °F. Liquidus	Solidus	Uses and Notes
5	95		592	576	For joints used at elevated temperature, say up to 250° F.
10–20	90–80		567–523	527–361	For coating (Terne plate) and joining articles such as heat interchangers
15–35	85–65		543–469	437–361	Automobile body solders used by wiping
37.5*	60	2.5	435	367	For joining pipes and cable sheath by wiping
38*, †	61.5	0.4 (0.1 As)	464	362	
38–40	62–60		462–460	361	Similar to previous one. Also for auto radiator cores and heating units
45	55		437	361	For auto radiator cores and for roofing seams
50	50		421	361	For general purposes
60	40		376	361	"Fine" solder. Used where application temperature is restricted
50	32	(18 Cd)	293	293	May be used for soldering pewter or readily fusible alloys
95		5	464	450	For electrical work and copper tubing joints
		(95 Cd 5 Ag)	750	639	For joints to stand at elevated temperatures
5 Ag	95 Pb		725	579	Used for joints to stand at elevated temperatures. Suggested for substitutes for tin-lead solders
2.5 Ag	97.5 Pb		579	579	
2.5 Ag	97.25 Pb 0.25 Cu‡		661	580	

* Should not be used on brass, zinc or galvanized iron.
† U. S. Patent 2,247,559.
‡ U. S. Patent 1,699,761.

the molten solder. Stearine is an active flux when used on lead or lead alloys. Scavenger fluxes such as zinc chloride, zinc-ammonium chloride, and ortho phosphoric acid tend to clean tarnished metals to be soldered as well as to permit soldering by the prevention of the formation of interfering oxides during the operation.

Rosin may be dissolved in alcohol or kerosene to make a flux solution. Zinc chloride salts or solutions usually containing some ammonium chloride are the most common fluxes. Frequently solutions containing 25–50% zinc chloride and 5–20% ammonium chloride with the balance water (all parts by weight) are used for general work. Several manufacturers market a very good paste flux containing by weight about 74% petroleum jelly, 20% anhydrous zinc chloride, 5% ammonium chloride, with 1% water as an emulsifying agent. Because of the corrosive nature of the resulting products of scavenger fluxes it is absolutely necessary to take effective steps to insure their removal from the finished product.

Methods of Heating or Application

The method of application of solder to the metals to be joined varies according to the character of the metals, their position, the size of the parts to be joined, the speed with which the operation must be completed and the shape, strength and appearance required by the finished work Heat may be furnished in many ways.

The surfaces soldered must attain the temperature of the molten solder during the soldering operation:

1. By the use of soldering iron or soldering copper.
2. By gas flames, blowtorches, or electric heating by resistance, induction or arc.
3. By dipping in solder baths.
4. By wiping, i.e., repeatedly pouring the just molten solder over the surfaces to be joined, and working the solder to shape while it is in a semimolten condition.
5. By sweating. (Heating parts until the solder runs between them.)

1. Soldering irons of various shapes are often heated in gas flames or furnaces. The irons (coppers) may be procured in various sizes and shapes weighing from about an ounce up to approximately thirty pounds. Irons electrically heated by means of an internal resistance unit are very convenient to use. Seams on sheet metal and soldering of electrical connections are examples where irons are used.

2. Massive articles which are to have solder applied to small parts of their surface areas are generally preheated and the solder melted with a blowtorch. Examples of such work are connections on commutators of dynamos and motors. Torches are also used for soldering electric wires together and to lugs. They are used for soldering sleeve joints on copper tubing.

3. Solder baths are used for dipping of automobile radiator cores or similar articles used for other heat transfer purposes. Solder baths are also used for soldering side seams of tin cans in automatic machinery.

4. Wiping is a means of making solder joints, mostly for lead cable sheathing or for lead pipes and fittings. The wiping method is in wide use because of the difficulty of otherwise sealing the bottom portion of a pipe joint and because its location often allows little working space, making it impossible to use a tool or mechanical device.

5. The sweating process has been found best where a great number of metal objects are to be soldered with great rapidity and when they are of uniform size, allowing the use of automatic machinery. This method is used for top and bottom seams soldered on tin cans. The sweating method may also be used for small articles with the application of a mixture of pulverized solder mixed with flux to a paste. The parts are moved on a belt through a furnace for heating.

Strength of Joints

Soldered joints on lead pipe or cable sheathing are usually stronger than the pipes or cable sheath. When strong metals are soft soldered and great strength of the joints is required, crimping, riveting or bolting of

seams before soldering is desirable. Thus a joint can be made stronger by relieving the solder of the load, and making the solder's major function that of hermetically sealing the seam.

Aluminum may be soldered with tin-rich alloys containing considerable zinc. One method is to rub the aluminum beneath molten solder in order to remove the aluminum oxide film and permit intimate contact or alloying of the metals. Brazing or welding is often preferred to soldering of aluminum.

Only lead-tin solders free from antimony should be used for soldering zinc or galvanized iron.

CHAPTER 14D

ELECTRIC-FURNACE BRAZING*

Processes, Assembly of Parts, Preparation of Material, Applying Brazing Metal, Selecting Brazing Metal and Flux, Limitations, High-Temperature Gradients, Tolerances, Strength of Bonds, Selecting Furnace Equipment, Gases Used.

Process Described

IN the electric-furnace-brazing process, assemblies are put together with brazing metal, in some such form as wire, applied near the joints to be brazed. The assemblies are then passed through an electric furnace in which a reducing atmosphere prevents the metals from oxidizing, frees the metals from any oxides present, and thus prepares the surfaces of the parts to be wetted by the molten brazing metal. In special cases, a solvent flux is added to assist the wetting action. When the brazing metal melts, it wets and creeps on the surfaces of the parts and is drawn into the joints by capillary attraction, surface alloying with the parent metal Upon transfer of the work to an adjoining controlled-atmosphere cooling chamber, the alloys when solidifying develop great strength, and the assemblies cool down to a temperature at which it is safe to bring them into contact with the outside air without danger of discoloration due to oxidation. In this manner, the assemblies are delivered from the furnace with strong, tight joints and clean, bright surfaces.

Figure 1 shows the manner in which a typical assembly is prepared for electric-furnace brazing, and how the brazing metal flows through the entire tight joint, forming a strong film of alloys with the parent metal.

Reasons for Using Process

Electric-furnace brazing is sometimes substituted for (*a*) machining from solid stock, (*b*) casting, (*c*) forging or (*d*) the use of a more expensive or time-consuming method of fabrication and (*e*) to gain specific benefits among which are those stated below:

(*1*) *Increased Life of Subassemblies and Reduced Service Costs.*—The high strength of the bond is such that the subassembly functions as one piece which has great resistance to vibration and impact and does not work loose in service.

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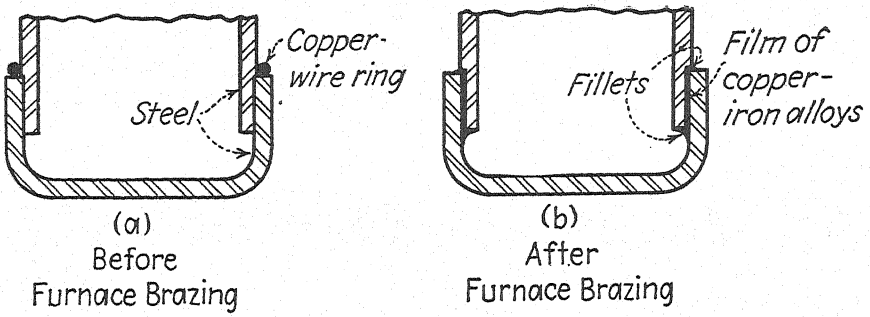


Fig. 1—Assembly Before and After Electric-Furnace Brazing

(2) *Reduced Production Costs.*—Savings in time, material, weight, space, rejections, inspection and finishing operations mean lower costs, while the quality of the product, in most cases, is actually improved.

(3) *Good Strength at Elevated Temperatures.*—Since copper, having a melting point of 1981°F. is usually employed as the brazing metal, the joint will have good strength at moderately high service temperatures, such as those encountered by steam-turbine diaphragm assemblies, finned Calrod heating elements, etc. The joint will also have good electrical and heat conductivity.

(4) *Pressure Tightness.*—The uniform distribution of brazing metal obtained through accurate control of quantity applied, and uniform time, temperature and atmosphere while the assemblies are in the furnace, yields thoroughly reliable gas-tight joints suitable for refrigerator floats, pistons, receivers and evaporators.

(5) *Accuracy of Shape.*—The freedom from distortion and residual stress occasioned so often by other joining methods involving localized heating or shrink fits, makes electric-furnace brazing the optimum method for many assemblies. Subsequent straightening or machining operations are reduced to a minimum.

(6) *Excellent Appearance.*—The parts come from the controlled atmosphere with surfaces clean, free of scale and usually free of flux, with the brazing metal as smooth fillets in the joint. Inexpensive to finish.

(7) *High Production Rate.*—Material can be kept moving continuously through a conveyor-type furnace. Furnaces can be built for small or large capacity. Many joints per assembly can be bonded simultaneously, with high production per operator.

(8) *Flexibility.*—Light parts may be brazed to heavy ones. Unlike metals can be joined as copper to steel,[8] low carbon steel to high carbon steel, cast iron to steel,[11] etc.

Examples.—Business- and sewing-machine subassemblies—formerly pinned or riveted gear clusters, cam clusters and levers with hubs; automobile and tractor parts formerly machined from solid stock, forged or cast—overrunning-clutch cams, rocker arms, brake toggles, track links; all are furnace brazed to have great strength and long life, with appreciable savings.

Holding Assemblies Together and Supporting Them in the Furnace

When putting assemblies through the furnace to be brazed, the relationship of the parts must be maintained, of course, from start to finish. One of the most important things to remember is the force of gravity. Assemblies have a tendency to fall apart after they become heated, and when the joints become loosened due to expansion. Also, the brazing metal naturally tends to flow downward more than in any other direction. It will creep horizontally or upward on the surfaces of the metal or in the joints, but it will flow downward quite freely and will collect at low spots if applied in excess quantities. Therefore, attention must be given to a means for holding the parts together within the furnace and setting the assembly up to direct the flow of brazing metal to the best advantage.

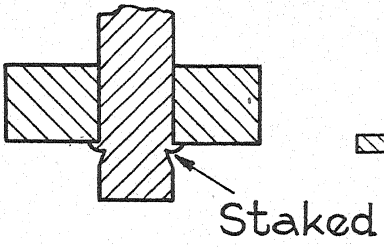


Fig. 2—One of Several Types of Staking to Hold Assemblies in Proper Relationship While Being Brazed

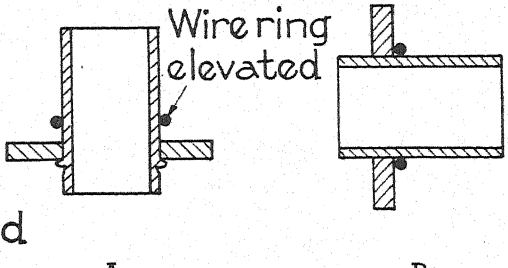


Fig. 3—Different Methods of Attaching Wire Rings to Parts Preparatory to Furnace Brazing: (A) Vertical axis, ring above joint. (B) Horizontal axis, ring close to joint.

Parts can sometimes be laid one on the other (but this lacks the advantage of indexing) or can be pressed together, spot welded, tack welded, staked (see Fig. 2), swaged, spun, expanded, peened, crimped, beaded, riveted, pinned, wedged, screwed, wound, overlapped, interlocked. These schemes are superior to the use of clamps or auxiliary supports for holding assemblies together because the latter retard the heating, increase the gross poundage to be heated and add straightening and replacement problems. Auxiliary weights are sometimes applied to assemblies to assure intimate contact at the joints. Another successful scheme for the same purpose, particularly for flat refrigerator evaporators, is to pull a partial vacuum on the assemblies when the brazing metal becomes fluid, to draw the plates together. Auxiliary fixtures are sometimes necessary for supporting assemblies in the proper position to direct the flow of brazing metal, to keep assemblies from tipping or rolling off the conveyor or trays and to keep them from touching and becoming brazed to one another. Such fixtures, when necessary, are commonly made of heat-resisting alloy strip, wire or castings; however, their use should be avoided wherever the assemblies can be made self-supporting.

Clean Surfaces Give Best Wetting Action

For best wetting action, the surfaces of assemblies should be perfectly clean. Heavy oil or drawing compounds should be removed, such as by a hot caustic wash, or by a vapor "degreaser." Carbon tetrachloride is occasionally used for cleaning parts. Light oil can sometimes be left on the parts, particularly if the oil distills readily and leaves no carbon deposit which would hinder wetting; however, even light oil should be avoided if possible.

Lead-bearing lubricants should be avoided because, in general, their presence completely prevents the creep of brazing metal into the joints. Bars, rods and tubing previously rolled or drawn with such lubricants have a skin which offers poor response to the wetting action and this skin should be ground, machined or scaled off before employing such stock in assemblies which are to be electric-furnace brazed. Furnace-brazed joints containing lead are extremely weak and brittle.

Oxides on the surfaces of parts at the joints should be pickled or otherwise removed preparatory to assembly.

Applying the Brazing Metal

A variety of forms of brazing metal can be used, such as wire, foil, slugs, filings, electroplate, molten spray and powder paste. The choice depends upon a number of factors which are related to the size and shape of the assembly, accessibility, quantity of brazing metal required, uniformity, quality of resulting bond and cost.

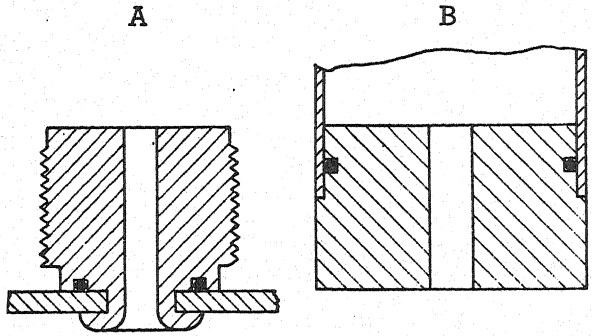


Fig. 4—Wire Rings Can Be Embedded Within the Joints in Grooves as Shown Here

The sketches shown in Figs. 3 and 4 give a few practical hints for locating wire rings. Figure 3-A shows the assembly with vertical axis having the wire ring elevated above the joint so that when the brazing metal melts, it will creep down the side of the tube and be drawn into the joint by capillary attraction before it has an opportunity to run on the horizontal flange away from the joint. Figure 3-B shows an assembly with horizontal axis with the wire ring pressed closely against the flange so that the brazing metal will be drawn into the joint when it melts, instead of running around the side of the tube and collecting at the bottom. Figures 4-A and 4-B show the rings held in grooves in the end and sides of parts to assure that the

brazing metal will be in place and to prevent its flow elsewhere than throughout the joints.

Wire and foil are used mostly because they assure uniform amount of brazing metal on all assemblies. Other forms such as electroplating, filings and powder paste are employed only occasionally, in cases where the brazing metal can thus be located more effectively than by using wire or foil.

Selecting the Brazing Metal and Flux

Selection of the most suitable brazing metal, and the form in which it is to be applied, depends upon a number of factors. For instance, it is possible to furnace braze assemblies made of practically any ferrous or nonferrous metal, or any combination of unlike metals, if suitable procedure is followed, and if care is taken to choose a brazing metal which

1. Melts and flows at a temperature somewhat lower than the melting point of the parent metals.
2. Wets the parent metals.
3. Is so placed that it will be able to creep throughout the joints.

The widest adaptation of furnace brazing is to steel assemblies, for which copper is generally used as the brazing metal wherever possible because it flows freely and gives strong, clean joints, without requiring a flux to help the flow except on parent metals difficult to wet. Copper generally wets low carbon steel easily. Some alloying constituents in steels, such as chromium, manganese, silicon, vanadium and aluminum form selective oxides when exposed to impurities in the furnace atmosphere at elevated temperatures, and these oxides can only be reduced by means of a solvent flux. If the constituents named should total in excess of 1% or 2% in the parent metal, a flux might be found necessary. Naturally the flux is avoided wherever possible because it is a nuisance to apply and to clean off after brazing. It should be mentioned here, perhaps, that nickel, because of its great affinity for copper, encourages the wetting action and is a favorable element to include in the parent metal.

Brass, which melts at a lower temperature than copper, is sometimes used as a brazing metal. But brass generally requires a flux coating to help it flow, it being necessary to prevent or clean up zinc oxides which tend to form on its surfaces. If the brass can be embedded within the joint, the flux can sometimes be avoided. The varying melting point of brass, caused by distillation and loss of its zinc, is sometimes a troublesome factor in furnace brazing.

Where wire rings are applicable to a brazing job, and bronze or other alloys containing zinc or other volatile components are further desired as the brazing medium because of temperature conditions, it has been found that the immersion of the rings in a tacky flux solution made from common borax with a small addition of anhydrous borax tends to set up a uniform film over the surface of the wire rings, which prevents the volatilization of zinc until the assembly reaches the normal melting point of the wire involved, at which time the film bursts and the brazing medium flows with approximately the same degree of freedom as is experienced in using pure copper in a copper brazing operation.

An alloy of phosphorus and copper,* and an alloy of copper, silver and phosphorus,† are self-fluxing on copper and flow freely at low temperatures. A flux is required when used on brass or bronze. These brazing alloys are recommended for non-ferrous parent metals such as copper, brass and bronze, on which they give strong, ductile joints, but they are not suitable for ferrous metals because the iron phosphide formed by the iron and phosphorus is extremely weak and brittle.

An alloy of copper, silver, zinc and cadmium,‡ is the lowest melting silver-brazing alloy available at present and is suitable for either ferrous or non-ferrous metals. It is almost always used with a special low-melting flux.§ It makes high-strength bonds, and is quite satisfactory, particularly on products which for one reason or another cannot well withstand elevated furnace temperatures, such as non-ferrous metals, cast iron or stainless steel.

Chapter 14B gives additional information on the use of silver-brazing alloys.

An aluminum-silicon brazing alloy with special flux is available for furnace brazing aluminum alloys 2S, 3S and 61S. The flow point is about 1160° F. An agitated air atmosphere is generally employed in the furnace. Highly satisfactory results are obtained in production.

High-melting brazing alloys in place of copper are sometimes used on steel, such as: 95 Cu, 5 Ni; 85 Cu, 10 Ni, 5 Fe;[10] 97 Cu, 3 Co;[10] and Cu, Ni, Zn.[4]

Limitations of Non-Ferrous Parent Metals

The electric-furnace brazing of non-ferrous parent metals with low-melting non-ferrous brazing alloys sometimes requires careful control of time and temperature. These limitations are the result of the rapid absorption of the brazing metal by the parent metal and vice versa, which restricts the distance of flow, and sometimes causes a "chewing" action in the parent metal. Also, limitations are imposed by the unstable flow point of such brazing metals because of selective melting, and the distillation of the volatile constituents such as zinc. To keep within these limitations, and to get rapid heating and cooling, fairly thin and uniform sections of parent metal are desirable. The brazing metal, in such cases, should be so located that the required distance of flow is short. Loose rather than tight fits generally give better flow. The silver-brazing alloy‡ is relatively free from the limitations named above, because of its exceptionally low melting point.

Use of High-Temperature Gradient

Sometimes a high-temperature gradient, or difference between the temperature of the furnace and the maximum temperature reached by the assemblies passing through the furnace, can be employed to gain advantages of quick heating such as rapid and thorough penetration of the brazing

* Phos-Copper.
† Sil-Fos.
‡ Easy Flo.
§ "Handy" Flux.

metal and a high rate of production. The use of a high-temperature gradient is generally restricted, however, to non-ferrous assemblies that are uniform in section so that all parts will heat uniformly and no part will exceed a safe temperature for either the parent metal or the brazing metal. Sometimes even higher gradients than those indicated in Table 1 can be employed successfully. For example, hollow nickel-silver knife handles are commonly bonded with low-melting silver-brazing alloys using furnace temperatures of 1800°F., although the assemblies themselves do not exceed 1300–1400°F. as a result of proper control of their time within the heating chamber and the fact that they heat evenly and rapidly.

When brazing assemblies are made of brass, some distillation of zinc from the parent metal is to be expected, which results in a surface coating of zinc or zinc oxide plus a residue from the flux which is needed to assure wetting by the brazing metal. If it is desired to restore the assemblies to their original luster, a hot-water wash and pickle will be required. Because of the necessity of cleaning the brass assemblies after furnace brazing even though a protective atmosphere is used in the furnace, some users of the process dispense with the protective atmosphere and use the normal air atmosphere instead, plus a generous supply of flux on the parts to assure wetting.

Table 1—Typical Brazing Metals and Suggested Fluxes

Brazing Metal	Flow Point, °F. Approx.	Furnace Temperature, °F. Approx.	Suggested Flux (If Needed)
Copper (any commercial grade)	1985	2000–2100	Flux§ anhydrous borax, or cryolite
Brass (60 Cu, 40 Zn)	1700	1750–2000	
Copper-phosphorus brazing alloy* rod or ribbon (7P, 93 Cu)	1382	1475–1550	Flux‡
Copper-phosphorus brazing alloy* ribbon (5P, 95 Cu)	1526	1550–1650	
Silver-brazing alloy (15 Ag, 80 Cu, 5P)[1]	1300	1400–1550	Flux†
Silver-brazing alloy (50 Ag, 15.5 Cu, 16.5 Zn, 18 Cd)[2]	1175	1250–1400	

* Phos-Copper.
† "Handy" Flux.
‡ Fluxine.
§ Several proprietary fluxes available such as Airco Marvel and Oxweld Brazo.
[1] Sil-Fos.
[2] Easy-Flo.

Tolerances—Tightness of Fits

In pressing parts together, the usual tolerances allowed in machining the parts naturally give variations in the amount of press fits which cannot be avoided. When brazing steel with copper, an effort should be made, however, to have snug, metal-to-metal fits at all times, if possible, both from the standpoint of assuring best strength and tightness in the joints, and preventing movement of the parts during handling around the shop. There is no actual limit to tightness of joints when copper brazing is used on steel assemblies, but increased tightness generally requires increased time in the heat to permit the copper to flow clear through the joints and nothing

is gained thereby. Sometimes a heavy press fit results in distortion of the parts due to stretching them beyond their elastic limit when hot; the resulting effects are opened up or weak joints. A good rule to follow for copper brazing steel assemblies is to use a maximum permissible press fit of about 0.001 in. per inch of diameter, and, for the other extreme, a maximum gap in the joint of 0.0005 in. Compromises preferably should be made in the direction of heavier press fits instead of larger gaps. A uniform sleeve fit should be provided, with intimate metal-to-metal contact throughout, rather than having only a line contact within the joint.

When brazing with lower-melting alloys, it is usually desirable to have a small clearance within the joint, ranging from 0.001 to 0.003 in., to permit the best flow of the brazing metal. The surfaces to be wetted should be perfectly clean and should be coated with a solution of flux before assembling to assure that the flux will be present within the joints and will not have to creep into the joints by capillary attraction.

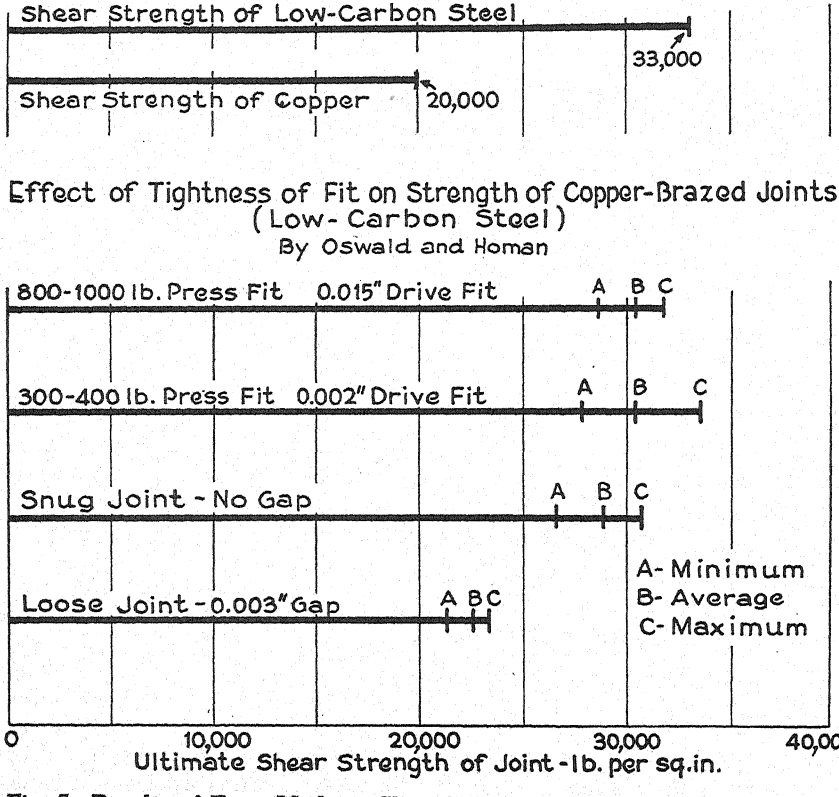


Fig. 5—Results of Tests Made to Show Relative Strength of Copper-Brazed Joints with Various Degrees of Tightness of Fit, Compared with (top) the Shear Strength of Annealed Low Carbon Steel and Copper

The greatest strength can be obtained with tight joints. Many of the values approach the strength of steel.

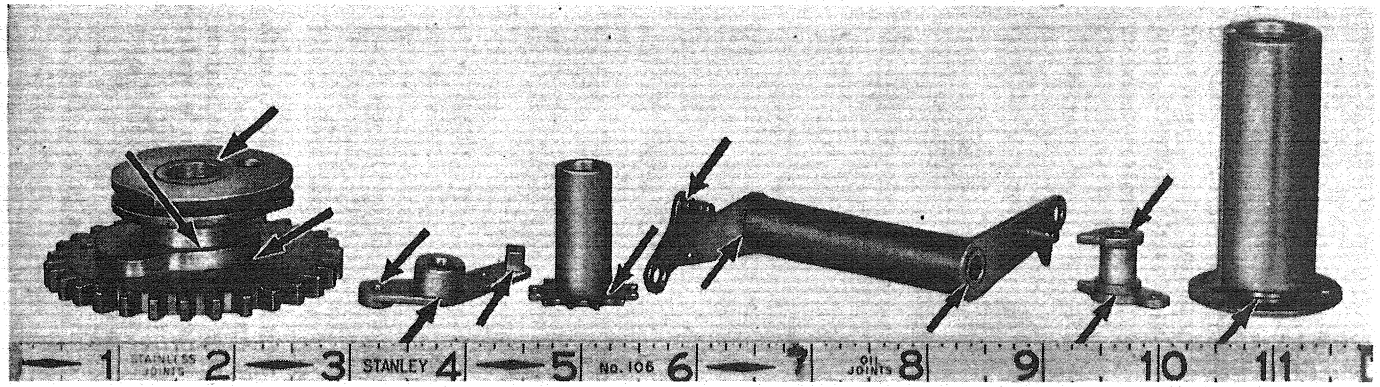


Fig. 6—Copper-Brazed Steel Subassemblies for Cash Registers, Formerly Riveted and Pinned
Advantages—greater strength, longer life, lower manufacturing and service costs.

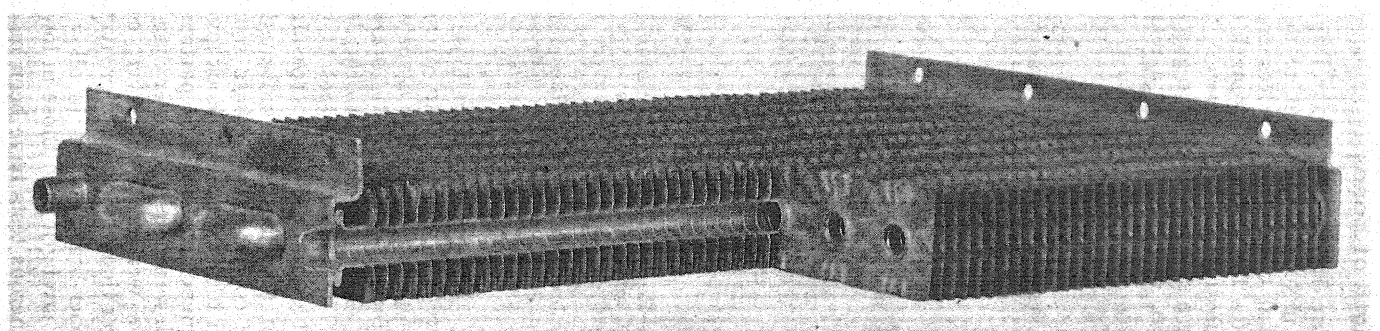


Fig. 7—Steel-Fin Condensing Unit Made up of Cupped Fins Telescoped Together
This assembly has 729 joints, all copper brazed in a single trip through a continuous furnace. Formerly made with copper fins sweated together. Now has lower cost, greater strength.

Strength of Bonds

Figure 5 shows the effect of tightness of fit on strength of copper-brazed joints in low carbon steel, as determined by Oswald and Homan of the National Cash Register Research Laboratory. Each bar in the chart indicates the ultimate strength of ten samples, with minimum, average and maximum values shown. The results illustrate the desirability of having a snug joint with no gap as compared to having a loose joint with 0.003-in. gap, there being a marked increase in strength with the snug

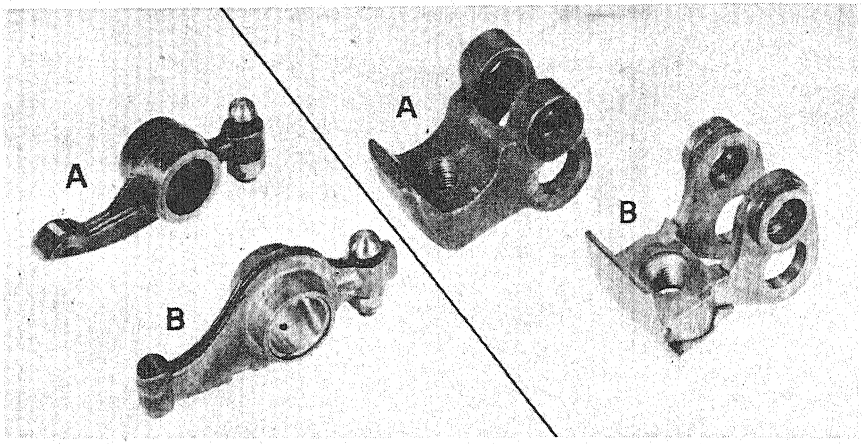


Fig. 8—Rocker Arm for Automobile and Tractor Motors
Formerly forged (A), now made of stampings and a screw-machine part furnace brazed (B), thus reducing machining operations, improving uniformity and life and lowering the weight and inertia.

Fig. 9—Brake Toggle for Tractors
Formerly made of cast iron (A) now made of stampings and a standard nut spotted together and furnace brazed (B) eliminating machining operations, reducing the weight 30% and cutting the cost 46%.

joints. But even with the loose joints, the strength is on the high side of the accepted average shear strength of copper. However, only six of the ten samples with 0.003-in. gaps were considered in the results because the other four were imperfectly brazed due to copper not filling the joints entirely. This fact points to the desirability of having a snug joint with no gap. The additional values plotted for heavy drive fits indicate no appreciable gain made by increasing the tightness.

Another series of tests indicated that heat treatment reduced the strength of the copper-brazed joints somewhat, the amount of reduction being related to the degree of shock given the samples upon entering the heating and quenching medium, particularly the latter. Values from a water quench were generally lower than those from an oil quench. In spite of this relative weakening, however, copper-brazed assemblies are still much stronger than their pinned or riveted predecessors.

Copper-brazed joints in alloy and high carbon steels have somewhat higher strength than those in low carbon steel.

Numerous tests have been made to determine the strength of furnace-

brazed joints using silver-brazing alloys and phosphorus-copper alloys Twenty-five thousand pounds per sq. in. in shear is usually considered a conservative ultimate value to use in making calculations. Much higher strength can be obtained under favorable conditions.

Factors Affecting Selection of Furnace-Brazing Equipment

A typical furnace-brazing equipment consists of an electrically heated furnace with heating and cooling chambers, along with the necessary power and temperature control, and an auxiliary device for supplying protective atmosphere to the furnace.

The most common type of brazing furnaces are the box-type, the mesh-belt-conveyor type and the roller-hearth conveyor type. Choice of the type of furnace to be used depends upon a number of factors, important

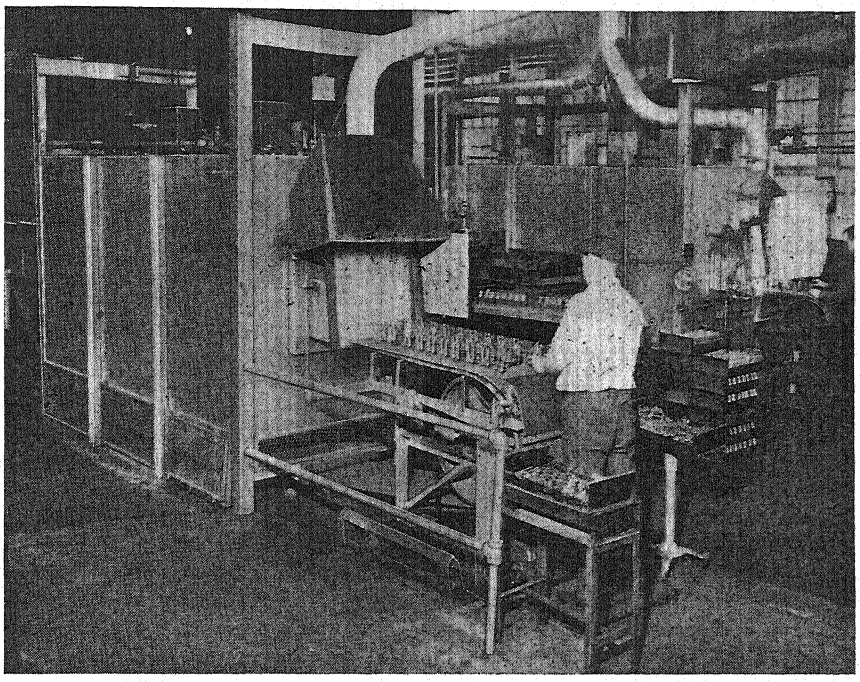


Fig. 10—The Mesh-Belt Conveyor-Type Brazing Furnace Is Eminently Suited for Continuous Production

It can be used either for furnace brazing or bright annealing, and features uniformity of time, temperature and atmosphere.

among which are the rate of production, the weight, shape and size of the assemblies, the price of the equipment and the cost of operation and maintenance. Just how these factors affect the choice is brought out in the discussions of the individual types below. (See Examples Figs. 6 to 9).

The Box-Type Furnace.—The box-type furnace has a heating chamber with cooling chamber attached and a sliding refractory door between to

serve as a radiation screen. It has outer-end doors which are also normally kept closed. Work is charged in trays or baskets and moved through intermittently. This type furnace has an advantage in that it is suitable for brazing assemblies of almost any weight—light, medium or heavy. It is best for low rates of production, or developmental work, because of its relatively small size, but in several cases multiple units have been installed for high output. The box-type furnace is relatively low in first cost and maintenance because there is no conveyor or mechanism involved. Another feature is its flexibility. It can be used not only for furnace brazing, but also for bright annealing or normalizing, scale-free hardening or pack carburizing.

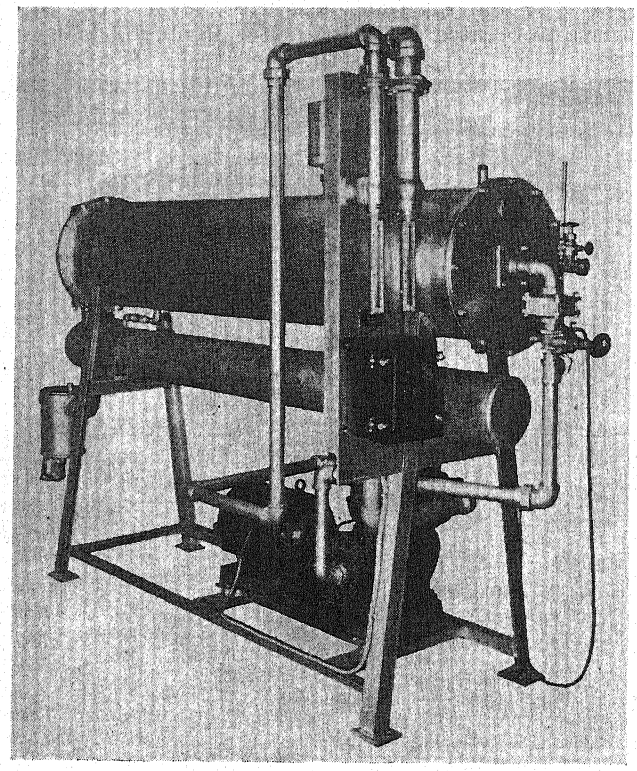


Fig. 11—Typical Atmosphere-Gas Converter for Partially Burning Hydrocarbon Gases to Produce a Suitable Gas for Use as Protective Atmosphere in Brazing Furnaces

Mesh-Belt Type Furnace.—The mesh-belt conveyor-type brazing furnace, Fig. 10, is built similarly to the box type in that it has a heating chamber with cooling chamber attached, but in addition, it is equipped with a conveyor with an adjustable-speed drive and a take-up mechanism. Assemblies to be furnace-brazed are generally loaded directly upon the belt which is supported by cast heat-resisting alloy rails, grids or hearthplates

in the heating chamber, and by the bottom plate of the liner in the cooling chamber. This type of furnace is best suited to relatively light-weight work, in quantities greater than those practical for handling intermittently in the box-type furnace or where control of time in the heat is critical.

Roller Hearth-Type Furnace.—The roller hearth-type furnace has the same arrangement of heating and cooling chambers as the box- and mesh-belt types but differs in the type of conveyor and carriers. The conveyor consists of a series of driven rolls throughout the furnace which extend crosswise through the furnace walls to bearings mounted on the outside of the casing. The rolls have individual sprockets driven by endless chains which run alongside the heating and cooling chambers. The assemblies to be brazed are sometimes loaded directly on the roll table if they are long and flat enough, but generally they are loaded on cast-alloy rails, or on fabricated trays made of sheet-alloy channels or cast rails tied together.

The roller-hearth furnace is ideally adapted to large-scale production. It is practical for brazing assemblies of light, medium or heavy weight. Maintenance is low because of long life of the rolls as they continuously turn and redistribute their stresses. The carriers have reasonably long life since they are free from any pulling or pushing stresses. The operating cost can be quite low by incorporating automatic charging and discharging mechanisms.

Gases Used for Furnace Atmospheres

Hydrogen makes an excellent atmosphere for brazing furnaces, as does also dissociated ammonia, which is 75% hydrogen and 25% nitrogen. However, practically all brazing furnaces use an inexpensive mixture of gases formed by the partial combustion of natural gas, coke-oven gas, butane or propane. The mixture produced by partial combustion contains approximately 16% hydrogen, 11% carbon monoxide, 5% carbon dioxide, 2% methane, remainder nitrogen. This mixture is reducing to iron and copper at furnace-brazing temperatures, and costs only 6 cents to 45 cents per thousand cubic feet, depending upon the cost of the hydrocarbon gas used.

A typical atmosphere-gas converter to produce a gas of this type, Figs. 11 and 12, consists of a combustion chamber with burner and fire check, a surface cooler for partially removing moisture from the products of com-

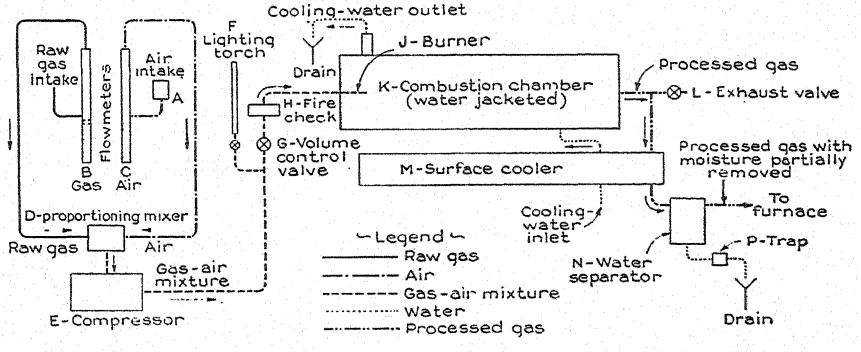


Fig. 12—Flow Diagram of Typical Atmosphere-Gas Converter

bustion, flow meters to indicate the input ratio and flow of air and gas, a means for adjusting and controlling the input ratio and a motor-operated compressor to deliver the mixture to the burner. Accessories are available for treating the gases as they leave the atmosphere-gas converter, if special requirements dictate that moisture, sulphur or carbon dioxide be removed before the gas enters the furnace. Other types of producers are also available for making directly, without additional treatment, gases for special purposes. For example, high-carbon or carburized steels require special atmospheres free from carbon dioxide and water vapor, high in carbon monoxide, to avoid surface decarburization and a resulting soft skin after heat treatment. Suitable gas producers are available for providing such atmospheres so that assemblies can be brazed and heat-treated to have maximum hardness all the way out to the surface.

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CHAPTER 15A

FACING OR SURFACING BY WELDING*

Definition, Nature of the Materials Applied, Procedure, Preparation of Work, Preheating, Fluxes, Thickness of Hard-Facing Deposit, Selection of Materials, Materials Which Can Be Hard-Faced, Hard-Facing Steel, Hard-Facing Cast Iron, Cooling Procedure, Finishing the Hard-Metal Deposit, Bond Between Hard-Facing Material and Base Metal (Gas), Selection of Iron Base Hard-Facing Filler Metal for Metal Arc Welding, Jigs for Hard-Facing, Advantages of Hard-Facing, Hard-Facing Applications.

Definition

HARD-FACING or surfacing is the process of welding or "overlaying" on wearing surfaces a facing, edge or point of metallic compound, thus producing a new surface which is exceptionally resistant to abrasion or corrosion, or both. By this method the original surface, which would be eroded or corroded rapidly in service, is protected by the layer of resistant alloy which is added. The process may be applied to new parts before their service or to old worn parts. In this chapter the term "Hard Facing" applies to the process whereby the final surface after treatment is harder than when in its original state. "Soft Surfacing" refers to the addition of metal or alloy so that the final result is a surface softer than the original. While hard-facing was originally applied only on oil well drilling tools and certain types of excavating equipment, other profitable applications were soon found in almost every field. Phenomenal growth of the process followed and today hard-facing is an important factor in the welding industry.

Nature of the Materials Applied

No single grade of hard-facing material is satisfactory and most economical for all applications. To meet adequately the various requirements of hardness, toughness, shock resistance and other qualities, various hard-facing alloys of widely different compositions have been developed. Broadly speaking, however, these may be divided into five groups.

Group 1.—Alloy steels consisting of an iron base with less than approxi-

* Prepared by a committee consisting of C. E. MacQuigg, Ohio State University, *Chairman;* N. J. Clark, Reed Roller Bit Co.; T. B. Jefferson, The Welding Engineer; J. R. Spence, Stoody Company; E. E. LeVan, Haynes Stellite Co.

mately 20% of alloying constituents are included in this group. Alloying constituents consist mainly of chromium, tungsten, manganese, silicon and carbon. These alloys are relatively low in cost and while not as hard as higher-priced hard-facing metals they possess greater toughness and shock resistance. However, they have greater wear resistance than any machine steels. Although not as long-lived as some other hard metals there are many advantageous applications for hard-facing materials in this group, particularly where low price is a controlling factor. Certain cheap and short-lived alloys, some of which are low alloy cast irons, may be listed in this group, but they find only minor application as hard-facing materials.

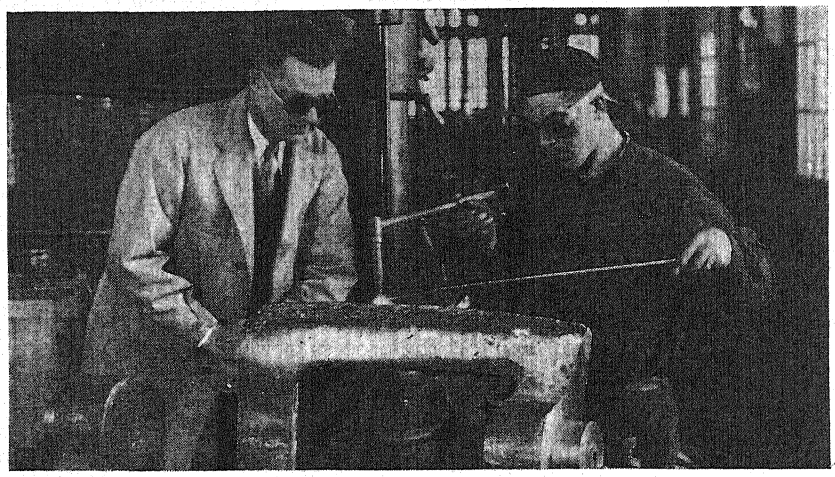


Fig. 1—The Combination of Abrasion- and Corrosion-Resistance of Hard-Facing Materials Protects This Mixer Arm for Mixing an Abrasive Mineral Substance in Hot Concentrated Sulphuric Acid

Group 2.—This group consists of iron-base alloys with more than about 20% of alloying constituents. Various amounts of chromium, tungsten, manganese, silicon and carbon and sometimes cobalt, nickel and other elements are contained in these alloys. Naturally these hard metals are higher priced than those of lower alloy included in Group 1, but they possess greater abrasion resistance and give longer service. As a rule they are not as shock resistant or tough as Group 1 hard metals, but are particularly adapted for use as the final wear-resisting surface, after the worn part is built up with high-strength rod. Due to the longer life of these surfacing compositions they generally are more economical in the long run than those in Group 1. Certain types of this group may have definite red-hard qualities but not to the extent of those mentioned in Group 3.

Group 3.—This group consists essentially of non-ferrous alloys with the principal ingredients cobalt, chromium and tungsten, but they may have other elements in lesser amounts. They are available in several different grades, all resistant to wear, but having a spread in strength and toughnes

which makes them suitable for a wide range of hard-facing applications. Certain types of this group like certain types of alloys in Group 2 have the unique property of red-hardness, that is, they retain their original hardness practically unimpaired at elevated temperatures.

Group 4.—The fourth group consists of the so-called diamond substitutes, the hardest and most wear-resistant (including red-hardness) of all hard-facing materials. Some of these are almost pure fused tungsten carbides ($WC + W_2C$), containing no alloying constituents. Others contain 90–95% tungsten carbides, the remainder being cobalt, nickel, iron or similar elements. The latter are added to impart toughness and impact strength to the tungsten carbides, the hardness of which, however, is slightly reduced as a result.

These so-called "diamond substitutes" are furnished in the form of small pieces which are affixed to the wearing surfaces of the objects to be protected, as oil well drilling bits and similar tools. Since these extremely hard carbide bodies are not melted by the oxyacetylene flame, they may be applied by means of other metals which "wet" them and hold them securely to the wearing surface in which they are thus imbedded. They may also be applied by the arc-welding process if care be observed to avoid striking the arc directly on the carbide pieces; the arc temperature is high enough to melt the pieces. The process of applying tungsten carbide particles to wearing surfaces is called "hard-setting." After "hard-setting" the surface is generally hard-faced with a rod of Group 5, thus combining the maximum of wear resistance and cutting ability in cutting edges as in the case of earth-drilling tools.

Group 5.—Crushed tungsten carbides of various screen sizes comprise the fifth and last group. These are furnished either (*a*) packed in steel tubes of various diameters, (*b*) fused to various sized strips of steel or (*c*) imbedded in a matrix or binder of steel in the form of a welding rod. All of these forms come in short lengths, which are applied like ordinary welding rods. Crushed tungsten carbides are also supplied loose, in granular or powdered form, to be sprinkled directly onto the wearing surface and attached to it as described above.

Procedure

Although hard-facing materials can be applied by any of the standard fusion welding methods, there are several factors which govern the choice of method for any particular application.

The oxyacetylene blowpipe or torch allows close control over the operation and produces a smooth deposit. Particles of scale and foreign matter are easily eliminated by this method, and edges and corners may be readily formed. This is particularly important where it is later necessary to grind the hard-facing to close tolerances.

Other advantages of the oxyacetylene process include the elimination of any loss of the hard-facing alloys by vaporization or spattering, close control of the oxidizing or reducing conditions of the atmosphere surrounding the molten metal, and more accurate control over the degree of penetration of hard-facing alloy in the base metal. This latter advantage is of importance especially with respect to the application of certain classes of hard-

facing materials, some of which should be puddled in, while others are flowed onto the base material at a "sweating" heat. The oxyacetylene process offers the facilities for producing either condition at the will of the operator. Its flexibility is thus a strong point in favor of its use for hard-facing.

The electric arc process has advantages in the matter of speed and great localization of heat during the surfacing operation and is used largely where a considerable quantity of metal is to be deposited. Suitable electrodes are available and the process is similar to the usual arc welding procedure.

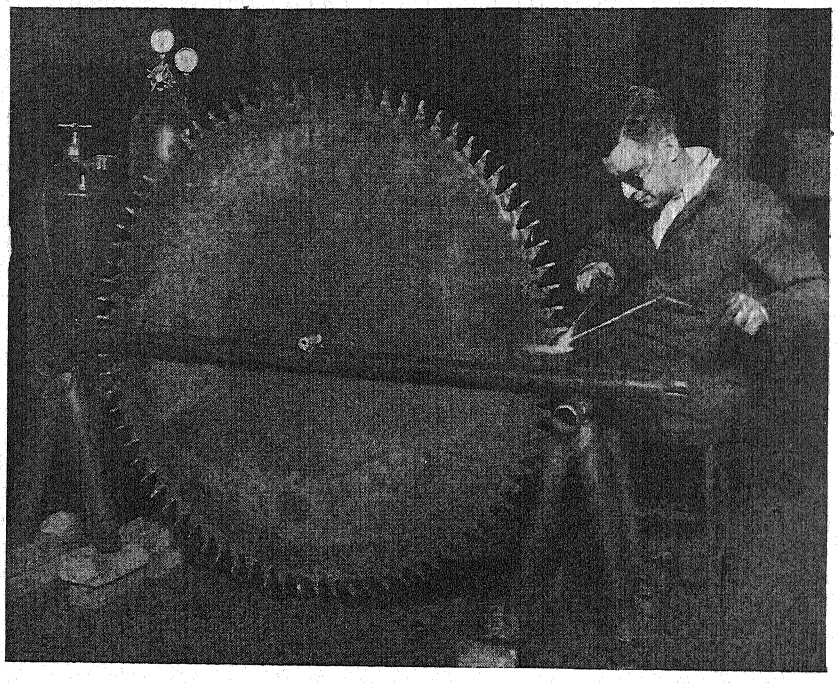


Fig. 2—The Versatile Hard-Facing Process Can Be Very Economically Applied to Slate Saw Teeth

Preparation of Work

All loose scale, dirt, rust or other foreign substances should be removed from the areas to be hard-faced, preferably by grinding, machining or chipping. If these facilities are not available, the surface may be cleaned with a file or wire brush, but this method often leaves scale or other foreign material which must later be floated out during the hard-facing operation. Any foreign material should be removed during the application either by a flux or by flicking out with the rod.

Where the hard-facing material is to be applied to a groove, corner or recess, it is preferable to have all corners well rounded, otherwise local over-

heating of the base metal may result. If but a small section of a part is to be hard-faced, a suitable shallow recess or indentation to receive the hard-facing metal may be prepared either mechanically or with the blowpipe or torch.

Preheating

The same general rules apply to preheating before hard-facing as apply to most welding operations. Parts are always preheated in cases where the application of the hard-facing alloy would otherwise cause them to warp or check, or where time and gases can be saved by preheating. Steels having more than about 0.35% carbon should usually be preheated. The optimum temperature of preheating is dependent upon the size and composition of the part, but usually it is between 700° and 1200°F.

It is generally unsatisfactory to hard-face steels which are in a hardened state. Thus stainless and alloy or other steels that are in the hardened condition should be annealed prior to hard-facing. If it is necessary or desirable to reharden the base material after the hard-facing has been applied, it should be quenched in oil—not water.

Fluxes

In the oxyacetylene application of hard-facing materials, fluxes are not ordinarily essential except in special instances. Sometimes a flux is of assistance where a second layer of hard-facing is necessary, or to help remove scale and oxide from the base metal. This is especially true when cast iron is the base metal. The principal advantage of a flux is that it floats on the molten puddle of deposited material, smoothing its surface and retarding the cooling action as well as protecting the metal from oxidation. In arc welding, the flux required is incorporated in the covered electrode as furnished by the manufacturer.

Thickness of Hard-Facing Deposit

In the vast majority of cases, hard-facing deposits range from $^1/_{16}$ to $^1/_4$ in. in thickness. The average is approximately $^1/_8$ in., but the proper thickness depends entirely upon the specific application. However, parts requiring a deposit thicker than $^1/_4$ in. are usually rebuilt with one of the alloys of Group 1, or with the material of which the base metal is composed, to within $^1/_{16}$ to $^1/_4$ in. of the finished size before hard-facing. The final hard-facing deposit is applied to a thickness allowing sufficient metal for grinding to finish size.

When the harder and more brittle hard-facing metals are used it is desirable to arrange the deposit in such a shape that any impact will be transmitted through the hard-facing metal into the tougher base metal. This is particularly true of corners and edges.

Selection of Materials

In order to intelligently select the correct hard-facing material for any particular application, the user should first determine those factors which cause the deterioration of the wearing part.

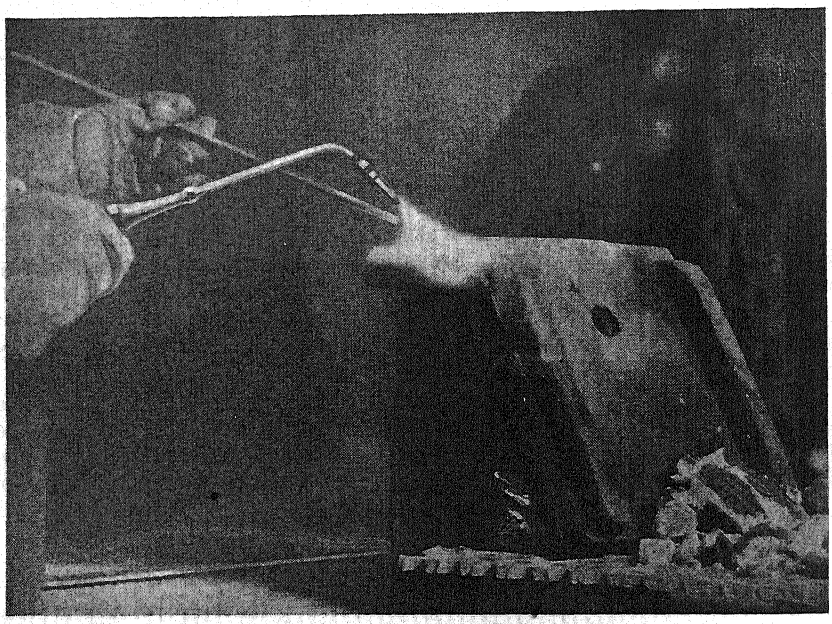


Fig. 3—Applying Hard-Facing Material to a Clinker Pulverizer Plow Arm with the Oxyacetylene Blowpipe

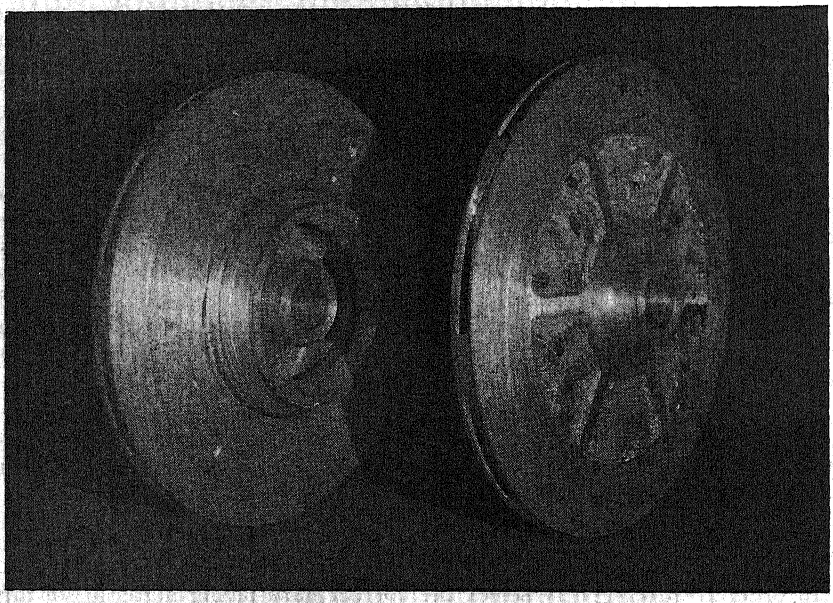


Fig. 4—Centrifugal Pump Runners, When Hard-Faced, Give Much More Economical and Efficient Service

In general, the attack on the part will involve one or more of the following: sliding or rolling friction, shock and impact, erosion and corrosion. Other factors, such as the smoothness of the deposit desired or, in handling sand, rock and gravel, the ability of the hard-faced part to form an efficient digging tool, also enter the picture. A word of caution must be added here respecting the *exact*, and not the *apparent*, nature of the service and of the facing material. The 12% manganese steel, such as Hadfields which would be covered in Group 1, affords a good example of what may be termed the difference between real and potential hardness. This steel as supplied does not have a high "mineral hardness," but when deformed it has the property of self-hardening. Therefore, parts which must operate against light abrasion, as in wear against sand or light scouring action, may give disappointing performance. On the other hand, if the use is against impact, as in a stone crusher where the surface may be pounded or hammered, the metal is automatically hardened and will prove its real merit.

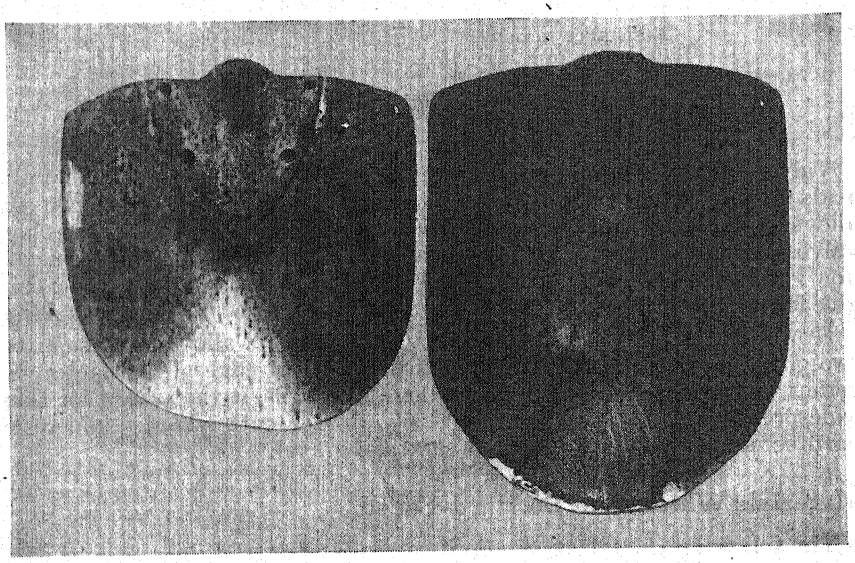


Fig. 5—Showing the Difference in Wear of an Ordinary Shovel and a Hard-Faced Shovel

Similar anomalies might develop in the case of certain corrosion services as with built-up areas subject to hot gases or fumes. Most of the compositions which are satisfactory for such service depend on automatic development of a highly protective coating (scale) which seals off further attack by virtue of its inert character; this scale may be so light as to be invisible in some cases. If, however, this protective coating is destroyed, the service record may be unsatisfactory. It is, therefore, best to be guided by experience or by the advice of reputable manufacturers in the selection of the material for a given application.

Once the various factors have been determined, Table 1 should serve as a fair guide in the selection of the proper type of material for the job. The numbers refer to the five groups of materials described previously. Taking the first heading, cold hardness, as an example, it will be seen from the table that hard-facing alloys of Groups 4 and 5 are the hardest* while those of Group 1 are the softest. Groups 2 and 3 are of intermediate hardness.

Three examples will serve to illustrate the use of this table. Mining equipment used for crushing rock and ore is subjected to constant battering and impact. Here resistance to shock and impact is all-important, with hardness only a secondary consideration, indicating a preference for hard-facing alloys of Group 1. In practice, these materials have proved to be the most suitable for this type of service.

Table 1—Relative Characteristics of Hard-Facing Deposits

Characteristic of Deposit	Group Number
Cold-hardness	4 5 2 3 1
Red-hardness	4 3 5 2 1
Resistance to impact	1 2 3 5 4
Corrosion resistance	3 2 1 4 5
Smoothness of deposit	3 1 2 5 4
Ability to withstand scouring	3 2 1 5 4
Thinness	3 2 1 5 4

Valves for handling high-temperature, high-pressure steam, gas, oil and acids must resist heat, erosion and corrosion. It has been found that the alloys of Group 3 work extremely well for the seating surfaces of these valves because of their red-hardness and corrosion resistance. No matter how ideal their other properties, alloys of Groups 4 and 5 would not be suitable for this service because of the non-homogeneous nature of their surfaces.

However, the very nature of the rough deposits of alloys of these latter two groups results in an extremely efficient digging edge. This factor, together with the greater hardness of these materials, is the reason for their widespread use on oil well drilling tools, dredge cutter blades and other parts coming in contact with earth, sand and gravel.

Materials Which Can Be Hard-Faced

The following classification affords a ready means of determining what metals or alloys can or cannot be hard-faced.

Medium and Low Carbon Steels.—All plain carbon steels up to about 0.50% carbon can be hard-faced.

High Carbon Steels.—Steels containing above 0.50% carbon can be hard-faced if reasonable precautions are taken to prevent the steel from cracking. In most cases, heat treatment is necessary to remove hardness and brittleness from the base metal both before and after hard-facing.

Low Alloy Steels.—Hard-facing alloys can be applied to low alloy steels in much the same manner as to plain carbon steels, provided the steel is not in the hardened state; if it is in the hardened state it should first be annealed. In a few cases, depending upon the composition of the base metal, heat treatment is required after welding.

* Note: Hard-facing materials of Group 4 and 5 have substantially the same properties since the essential difference between the two is in the size of the tungsten carbide particles.

High-Speed Steels.—The hard-facing of this group of steels is not generally recommended. They can be hard-faced without difficulty in so far as technique is concerned, but shrinkage cracks and strain checks render the hard-faced piece valueless in a good many instances regardless of heat treatment.

Stainless Steels.—Stainless steels, including the high chromium steels and the 18–8 chrome-nickel steels can be hard-faced. However, a knowledge of the physical properties of the particular type of stainless steel is necessary, otherwise difficulty may be experienced due to brittleness or lessened corrosion resistance. The usual precautions due to the high coefficient of expansion of the 18–8 steels should be observed.

Manganese (Hadfield) Steel.—This steel is hard-faced by the metallic arc-welding process only.

Gray Cast Iron.—Cast iron can be hard-faced, but the method of application is somewhat different from that for steel due to the lower melting point of cast iron.

White Cast Iron.—White or chilled iron can be hard-faced in small parts; on larger parts heat treatment is sometimes necessary and a careful study of the design and location of chills is necessary, since preheating may soften some of the chilled areas.

Alloy Cast Irons.—The same procedure can be used as for hard-facing ordinary gray cast iron.

Monel Metal.—Monel metal can be easily hard-faced.

Brass and Bronze.—These copper base alloys are difficult to hard-face because of their low melting point. In rare instances, however, heavy sections which have been preheated to a red heat can be hard-faced. Hard-facing is not recommended.

Copper.—Because of its low melting point and high heat conductivity, copper is hard-faced only with difficulty. Preheating is absolutely necessary.

Hard-Facing Steel

Group 1 (Iron Base—Less than 20% Alloying Constituents).—In applying hard-facing welding rods of Group 1 to steel, a flame containing a slight excess of acetylene should be used, since a neutral flame causes boiling and sometimes produces an unsatisfactory result. Penetration of the hard-facing alloy in the base metal should be from $^1/_{32}$ to $^3/_{32}$ in., depending on the type of rod used. Of course, for economy the hard-facing deposit should not be puddled in so deeply that it is practically buried in the base metal. In the cases of the composite welding rods, it is important that the rod be oscillated slightly to mix the alloy thoroughly with the steel casing.

The hardness of deposited hard-facing metals of this class depends largely upon the amount of acetylene used in the flame and upon the rate of cooling. A greater excess can be used if an exceptionally hard deposit is desired. A quenched austenitic type of deposit is not as hard as, but is tougher than, slowly cooled metal. Rods in this group are available for both arc and gas welding.

Sometimes the method known as the transition layer is used, that is, below the surfacing required or desired, is placed a metal of another kind. An example of this is the use of 18–8 stainless steel on manganese steel as the intermediate layer and then the hard-facing metal layer is placed on top of the 18–8 as the final surface. As a rule, a study of the various metals available and their general performance will enable surfacing jobs to be done so that the requirements may be met.

Group 2 (Iron Base—20 to 50% Alloying Constituents).—It is generally recommended that alloys of this group be applied to steel by thorough amalgamation. A carburizing flame should be used with the excess acetylene streamer approximately twice the length of the inner cone. Usually it is

advisable to heat the base metal a little beyond the surface "sweating" condition so that a thin surface layer is actually melted. Since the hardness and other physical properties of these alloys remain practically unchanged within a considerable range of carbon content, penetration of the

Fig. 6—Surfacing Material Applied Around Port on Engine Cylinder Head

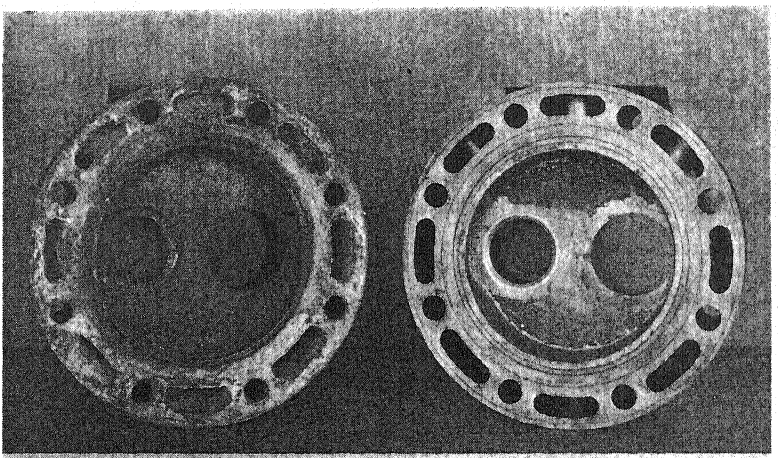




Fig. 7—Hard-Surfacing Worn Wagon Track Shoes

base metal has little or no effect on the quality of the deposit. Rods in this group are available for application by both arc and gas welding.

Group 3 (*Non-Ferrous Cobalt-Chromium-Tungsten Alloys*).—The non-ferrous alloys should be applied, when possible, without excessive inter-alloying with the steel base. In this manner, it is possible to avoid diluting the alloys with iron and thus preserve the red-hardness and abrasion-resisting properties of the alloys unimpaired. The flame for hard-facing with the non-ferrous alloys must contain an excess of acetylene, and should be adjusted so that the flare or outer cone denoting an excess of acetylene extends at least double the length of the inner cone. This amount of excess acetylene will satisfactorily prepare the base metal by producing a good sweating surface to allow free spreading of the hard-facing metal, and preventing oxidation ahead of the fusion zone.

A small area of the surface to be hard-faced should be brought to a sweating temperature, and the end of the rod brought into the flame and allowed to melt and spread evenly over the sweated area. The hard-facing material, when applied at the proper temperature, "wets" the base metal and spreads out readily over the "sweating area." The rod should not be stirred or puddled. Additional alloy is spread in the desired direction by means of the welding flame. The metal melted from the end of the rod should be added to the molten metal that is already in place on the surface of the work. Doing it in this way and spreading the metal already in place will insure a proper and continuous bond with the base metal.

It is usually possible and preferable to build up the coating to the desired thickness in one operation. As a general rule, no flux is necessary when the non-ferrous alloys are applied to clean steel. Rods are available for application by both arc and gas welding.

Group 4 (*Tungsten Carbide Inserts*).—Tungsten carbide inserts, well known as diamond substitutes, are now in almost universal use for hard-setting oil well drilling tools.

In general, the procedure involves, first, cutting grooves in the steel base metal by means of either an oxyacetylene cutting blowpipe or a forging hammer. The size and spacing of the inserts will vary with the type of drilling tool. The steel in one groove should be melted with an excess acetylene flame. After one insert is fastened to the end of the rod by a "wetting" action the place in which it is to go should then be heated until melted while the insert is held in the flame. When the surface is brought to a molten state the insert is pushed into position. Finally the insert should be completely covered over with the steel welding rod. This operation is repeated for another groove until the desired number of inserts have been set. Maximum wear resistance is obtained when a final coating of hard-facing alloys of Group 5 is deposited over the inserts.

Group 5 (*Crushed Tungsten Carbide with Steel Binder*).—These materials consist essentially of two types—composite and tube—both of which are applied in much the same manner. When the operation is performed with the oxyacetylene process, a flame containing a small excess of acetylene should be used. The application should be made without penetrating as deeply into the base metal as in ordinary steel welding. A certain amount of stirring with the rod is necessary to obtain the most even distribution of the deposited metal. Molten metal from these rods flows

less freely than that from ordinary welding rods, due to the presence of the refractory tungsten carbide particles which are not melted during the application. The deposit should be kept molten for a short time only. The welding tip should be large enough to produce a flame which will supply the required amount of heat with the pressure low enough to avoid blowing the molten metal. Rods in this group are available for application by both arc and gas welding.

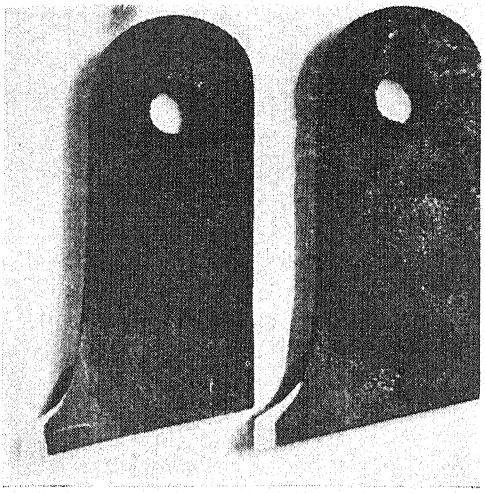


Fig. 8—Hard-Facing Increases the Life of Mill Hammers from 700 to 1000%

Hard-Facing Cast Iron

Group 1 (Iron Base—Less than 20% Alloying Constituents).—In applying materials of this group to cast iron, a small area at a time should be heated with the blowpipe and the surface crust broken with the end of the rod. A little puddling is usually necessary and a good flux is often helpful. Because of the low melting point of cast iron, considerable care should be taken when working up thin surfaces or edges and corners. Other than this, hard-facing cast iron with the materials of Group 1 is similar to hard-facing steel.

Group 2 (Iron Base—20 to 50% Alloying Constituents).—These alloys are applied to cast iron in essentially the same manner as they are applied to steel.

Group 3 (Non-Ferrous Cobalt-Chromium-Tungsten Alloys).—These alloys should be applied to cast iron with a little less acetylene in the flame than is used for steel. Since they do not flow as readily on cast iron as on steel, it is usually necessary to break the surface crust with the end of the rod. A cast-iron welding flux is often helpful. It is usually best to weld a thin coating first and then go over it again and build up to the desired thickness. These alloys have approximately the same melting point as

cast iron, and care must be taken not to melt the base metal too deeply. If the cast iron is very thin, it will prove advantageous to back it up with wet asbestos or carbon paste to avoid melting it.

Groups 4 and 5 (Tungsten Carbide Inserts and Rods).—These hard-facing materials are rarely, if ever, applied to cast iron in practice. In those few instances where they are, the technique follows generally along the same lines as the procedure for their application to steel.

Cooling Procedure

Most satisfactory results are obtained after hard-facing if the part is cooled slowly to avoid setting up stresses in the deposited metal. A little more care is necessary than is employed in ordinary welding procedures. If no further heat treatment is necessary, the hard-faced piece may be cooled under the blowpipe or torch, or can be dropped into dry lime or other packing material and covered over. If, however, the piece is to be heat treated to improve the strength of the steel base metal, and to produce a finer and stronger grain structure, the hard-faced piece should be heated and then either quenched in oil or normalized by cooling in air. Metals of Group 1 may sometimes be quenched in water—but not metals of other groups.

Finishing the Hard-Metal Deposit

Groups 1 and 2 (Iron Base Alloys).—These hard-facing materials may be shaped to a certain degree while they are in their plastic temperature range. When a deposit of one of these alloys is heated to within 200 to 300°F. of its melting point, it may be scraped off in thin layers with an old file, or other implement, until the deposit has been brought down to the required size and shape. Peening while hot is sometimes advisable. Ordinarily, alloys of Groups 1 and 2 are very difficult, if not impossible to machine. If they cannot be brought down to their finish dimensions exactly by "hot filing," as this procedure is known, grinding is necessary. Recommendations for grinding wheels for various operations may be obtained from literature published by the various manufacturers of these hard-facing materials.

Group 3 (Non-Ferrous Alloys).—All grades of the non-ferrous hard-facing materials with one or two exceptions are too hard to be economically machined, but they can be finished by the hot-filing method described in the preceding paragraph or by grinding. The wheel speed when grinding these alloys should not be less than 2800 or more than 4200 surface ft. per min. Higher speeds, or speeds within this range with wheels that are too hard, may cause grinding checks. Wheels recommended for specific purposes may be obtained from the manufacturers of these alloys. One or two grades of this group may be machined at slow speeds and light feeds with tungsten carbide cutting tools.

Groups 4 and 5 (Tungsten Carbide Inserts and Rods).—The best results in grinding parts hard-faced with these materials will be obtained by using wheels designed for this particular work only. Grinding wheel manufacturers should be consulted and their recommendations followed as to

proper grade, grain and bond. All wheels should be kept sharp by frequent dressing to avoid glazing and checking of the hard-faced surfaces.

Bond Between Hard-Facing Material and Base Metal (Gas)

The bond obtained between the hard-facing material and the base metal is as strong and sometimes even stronger than the hard-facing deposit itself. Rarely, if ever, do hard-facing metals break away from the base metal at the bond if the proper materials and method of application have been used.

On many hard-facing applications, surface cracks are not detrimental since they usually run only through the deposited metal and stop at the base metal. If surface cracks are present and undesirable they can generally be repaired by heating the metal along the crack to a red heat, then melting it down into the crack and allowing it to close in slowly, meanwhile adding a few more drops from the welding rod. The heat should be drawn slowly away from the hot spot into the body of the base metal to prevent quick cooling and subsequent cracking and the part should be cooled slowly in lime, ashes or mica.

Selection of Iron Base Hard-Facing Filler Metal for Metal Arc Welding

In choosing the proper electrode for repairing worn or broken equipment, it is necessary to bear in mind the analysis of the metal being welded and the conditions under which the equipment operates. Failure to consider either of these factors will be reflected in the quality of the result obtained.

Electrodes are available for the deposition of different types of surfaces, each having its own characteristic. These electrodes may be grouped according to the ability of their deposits to resist:

1. *Impact*, which may tend to deform the surface of the metal or cause cracking or chipping.
2. *Abrasion*, which may be either a grinding action due to contact of metal with sand, gravel and similar abrasive materials; or a sliding, rolling or rubbing action of one metal against another.
3. *Impact and abrasion in combination*, with one moderate, the other severe, or both moderate or severe.
4. *Corrosion*, including actions of various chemicals, water and also oxidation or scaling at elevated temperatures. The corrosive media may be gaseous or liquid, or gaseous and liquid in combination.
5. *Temperature*, which may exist in conjunction with each of the above conditions.

Where shock and abrasion are factors, deposits may be air-hardening alloy steel. Hardness of the deposits ranges between 40 and 45 Rockwell C. Depending on carbon content of the supporting metal, hardness may run as high as 52–55 Rockwell C. Parts of equipment subject to sliding, abrasive action, batter or repeated pounding and impact may be surfaced effectively with this type of deposit.

Where the surface is subject to sliding actions, and the parts must retain their dimensions under high temperatures, a deposit equivalent to high

speed tool steel may be obtained. Such deposits, in original condition, will have hardness of 50–55 Rockwell C, provided they are not diluted too much by the supporting metal. When this dilution is kept to a minimum, as by using two beads, hardness may be as high as 60–62 Rockwell C. The surfacing metal retains its characteristics up to rather high temperatures, approximately 1000°F., provided the proper materials have been selected for the hard-facing operation.

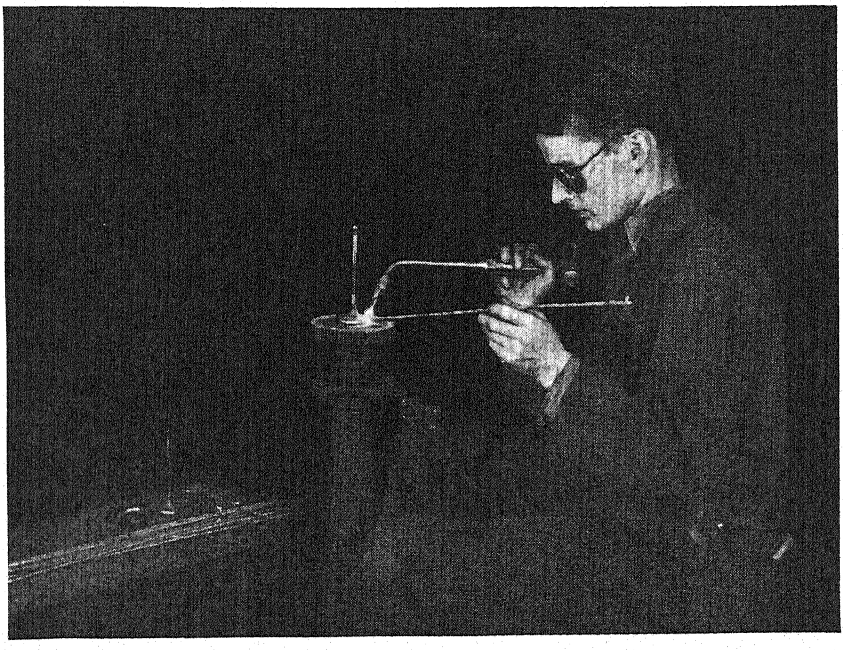


Fig. 9—Applying a Hard-Facing Material to an Automotive Valve

Jigs for Hard-Facing

Many hard-facing operations, both in production and repair, are facilitated by work-holding devices and special jigs. Some operations which otherwise might not be practical, can be rapidly and efficiently accomplished through the use of auxiliary appliances. Savings derived from an operation are often greatly increased by the reductions in labor, time and handling thus made possible. Several typical examples of jigs will suggest ways of facilitating the hard-facing operation.

Several coal companies have found it much easier and faster to hard-face undercutter bits when they are set up on a jig. Either a "merry-go-round" jig or a moving table may be employed to good advantage in this application. At one coal company which uses the former method, 450 bits are hard-faced by one operator in an hour.

A well-designed jig and nose plate help tremendously in obtaining prop-

erly shaped plowshares. With the aid of these accessories, a plowshare may be hard-faced and its nose shaped in one operation. A further aid in plowshare work is the use of a jig designed to swivel as well as turn the share completely over. A share clamped in such a jig can be readily adjusted so that the area on which the welding operator is working is always level. Rotating jigs or chucks set at a convienent angle are a great aid in hard-facing steam valves, dies, automotive valves and inserts and other small parts where an even deposit is required. Even simple rests on which the work can be placed are often helpful in allowing the welder to work in a comfortable position. Most jigs are homemade affairs, adapted specifically to the jobs in question, and a little ingenuity on the part of the operator will aid him in turning out work more quickly and accurately with greater economy and convenience.

Advantages of Hard-Facing

In many applications where two metal parts are rubbing together either clean or in the presence of abrasive material, it has been found that hard-facing one of these objects will increase the life of both pieces. It is true that the maximum results will be obtained by hard-facing both surfaces, but in some cases this is not feasible as one of the surfaces may be so large or so inaccessible as to make hard-facing impractical. The hard-facing of only one component in a pair undergoing friction may result in greatly increased length of service. The explanation of this apparently lies in the fact that hard-facing on the surfaces reduces friction and also reduces any lapping effect that would be caused if one of the surfaces picked up and retained abrasive particles which would then abrade the other surface. A large number of applications that have given this result show that it is unsafe to conclude that hard-facing one part will produce increased wear on the other.

Prolonged life results directly in fewer replacements of faced parts. In many cases, replacing a worn part means not only a loss in production due to a shut-down, but also a loss arising from idle labor during the replacement. Thus, a reduction in down-time for a machine means an increase both in production and efficiency. Particularly with larger equipment, such as dredges, power shovels and the like, tie-ups are very expensive.

For example, such parts as blades or teeth on machines for cutting earth formations must be kept sharp to be efficient. Plain or unfaced blades or teeth have to be removed, resharpened and reinstalled as often as they become dull. Hard-faced blades and teeth, however, are designed to wear so that they do not become dull, but remain sharp and operate efficiently until they have worn away entirely, at a much slower rate.

It is a well-known fact that usually the maximum toughness and hardness of metals do not go hand-in-hand. Many tools, implements and machinery parts must be, by their design or the kind of work they are to perform, very strong and tough. If such parts are made of tool steel and heat treated, a compromise between hardness and toughness must generally be accepted. With parts designed for hard-facing, however, a steel may be selected for the base or parent metal that is expressly suited for strength requirements and shock resistance. Only the strength and cheapness of the bulkier base metal need be considered; then the wearing surfaces are

hard-faced with a suitable abrasion-resistant material, thus creating a composite part, which possesses both strength and hardness where needed to a maximum degree. In many cases, plain carbon steels may be used for the part. These have the necessary strength, shock and fatigue resistance, and at the same time effect considerable savings in the higher-priced alloy steels.

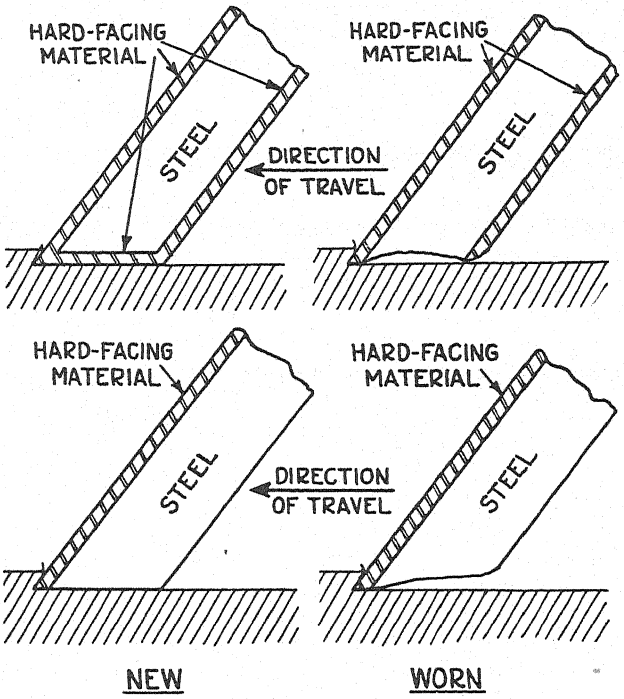


Fig. 10—Illustrating Proper Hard-Facing Procedure to Secure Self Sharpening Effect of Earth Working Equipment

Many parts which formerly were sent to the scrap pile now are rebuilt, hard-faced and returned to service at a cost considerably less than that of replacing with new parts. Such hard-faced reclaimed parts are much superior to plain new parts in any case, as they will outwear them several times and operate more efficiently. Also, this practice makes it possible to reduce the stock of parts kept on hand for emergency and general replacements.

Still another important economy, but one which is difficult to evaluate accurately, results from the fact that hard-faced parts remain in better condition. As equipment begins to wear, its effectiveness as an individual producing unit is usually lowered. Operation becomes slower; output and efficiency are decreased; frequently more power is required to drive the machine in order to maintain satisfactory performance.

The major cost-reducing features of hard-facing may, therefore, briefly be summed up as follows:

1. Longer life of equipment.
2. Fewer replacements with resultant savings in maintenance costs and lost production time.
3. Utilization of cheaper base metal for wearing parts.
4. Salvaging or reclaiming of worn parts.
5. Savings in power consumption.
6. General increase in operating efficiency.
7. Maintenance of desired dimensions within close limits and at low cost.
8. Flexibility in providing hard surfaces at desired points.

Hard-Facing Applications

Only a few typical examples of hard-facing procedures and the economies resulting from their use can be described here. The following short survey of the more important fields of application, together with typical uses in these fields, will help to give an indication of the extent of hard-facing in these industries.

Agriculture.—The agricultural industry was one of the first to adopt hard-facing. Plowshares, one of the farmer's most important tools, last three to seven times longer when hard-faced. In addition, hard-faced plowshares require less sharpening, they will maintain a keener cutting edge and, therefore, they save considerable power and do a much more efficient job of plowing. Tests carried out by several State University Agricultural Experiment Stations have definitely proved that plowshare costs are reduced at least one-half by hard-facing.

Some other typical examples of hard-faced agricultural implements are corn planter runners, tractor treads, subsoil teeth, cultivator spades, threshing machine cylinder and concave teeth, beet puller points, potato diggers, hay mill and pulverizer hammers.

Automotive.—The automotive industry, a pioneer in many metallurgical improvements, has adopted hard-facing for not only its manufacturing machinery, but also for wearing parts of bus and truck motors. Probably the most outstanding example of the use of hard-facing material in the automotive field is the armoring of exhaust valve seats. Several manufacturers of heavy duty trucks and buses have standardized on hard-faced exhaust valve seat inserts, because these seats last longer, require less attention and reduce valve grinding and adjustment to a minimum. Other advantages are lower gasoline consumption, lower compression losses and increased power, mileage and all-around motor efficiency. Recently, fleet owners have specified hard-faced valves as well as hard-faced valve seat inserts.

Other representative automotive applications of hard-facing are clutch parts, including release yokes, pressure plates, throw-out fingers and release bearing housings, water pump shafts, transmission shifting fingers and valve stems.

Aircraft.—This new industry has been quick to grasp the possibilities of hard-facing and today practically all aircraft valves and valve seats are hard-faced with Group 3 alloys. By prolonging the life of these valves

and valve seats through hard-facing, the flying life between interruptions for valve repair and replacements has been lengthened and the operating costs have been reduced, because the hard-faced valves and valve seats perform their proper function so much longer, assuring full continuous engine power. The conditions in aircraft engines are very severe and hard-faced valves and valve seats have proved their ability to resist the severe conditions of aircraft operation and the corrosive effect of hot exhaust gases at temperatures probably as high as 1500°F. The engineering department of one of the large airlines reported to a valve manufacturer that hard-faced valves removed after 4080 hours of service were still in excellent condition, even to the extent that the grinding and finishing marks could still be seen. This compares with the usual run of about 500 hours with high grade steel valves that have not been hard-faced. The time of 4080 hours in the air means the remarkable total of 714,000 air miles of efficient, uninterrupted service.

Brick.—One of the first uses for hard-facing in the brick industry was on feeder shoes in brick machines. Pug mill mixing knives, augers and wearing strips, extrusion dies and cutting table knives all have a far longer useful life when hard-faced.

Cement.—The cement industry is one of the largest users of hard-facing material. Cement manufacturing equipment is necessarily subjected to extremely abrasive conditions. The raw materials, cement clinker and pulverized cement, wear away the best steel in such a short period that, prior to the advent of hard-facing materials, the maintenance of many parts in the cement plant was a real problem.

Hard-facing alloys are also used to prolong the life of pipe bends in lines carrying either pulverized cement or mixed concrete. It is now standard practice to cut the pipe bend lengthwise with an oxyacetylene cutting torch, hard-face the inside wall on the outer part of the curvature and weld the two parts of the pipe back together again. This application is most economical from the standpoint that in order to replace the pipe, the entire cement plant would have to be shut down. With hard-faced pipe bends, practically no replacement is necessary.

Coke and Gas.—The coke and gas industries have profited by the application of hard-facing materials. Considerable savings have been made through the use of the process and many parts of machinery used by this industry are hard-faced as a standard procedure in the maintenance programs of plants. For instance, coke pusher shoes are regularly hard-faced in many plants.

Several steel companies have standardized on hard-faced water-cooled pokers for continuously stirring the coal in gas producers. These pokers are subjected to such severe heat and abrasion that the life of an ordinary 8-in. diameter steel poker is only about three months. Hard-faced, these pokers last over two years.

Excavating.—In few industries is equipment subjected to as severe conditions of abrasion as in excavating. Probably the most extensive use of hard-facing in excavating is for protecting dipper bucket teeth.

Iron and Steel.—Abrasion is one of the greatest problems encountered in the iron and steel industry. Steel parts clashing or even rubbing together, especially at red heat, become worn so rapidly that replacement

becomes a frequent necessity. Wherever lubrication is impossible or unreliable, especially under conditions of severe heat or abrasion, the use of hard-facing material has proved highly economical.

Machinery.—Machine shop practice offers many opportunities for effecting savings by the application of hard-facing. Lathe centers, guides, clutch cams, trips—these and a number of other small machine shop parts subjected to wear, operate with greater accuracy, more economy and fewer interruptions when hard-faced with a wear-resistant material.

Oil and Gas.—It is interesting to trace the parallel development of the hard-facing process and better oil well drilling tools—tools of more intricate design and made of better materials. It is a long step from the shop dressed and tempered fishtail to the cast or forged bits having multiple cutting and reaming blades. Such intricate tools as are today available would probably never have been feasible without the extra long life imparted to them by hard-facing materials.

Power.—For a long time hard-facing materials have been applied to various parts of equipment used by the power industry. There has been a definite trend toward the use of hard-faced seating surfaces in valves handling high-temperature, high-pressure steam. Hard-faced valves reduce power losses to a minimum and are free from scoring and wire drawing even under the severe conditions of drip or throttling service. When properly deposited on the base metal, the wear-resistant alloys are not subject to warpage or distortion from repeated heating and cooling. In addition, the low coefficient of friction of the alloys employed is especially valuable in certain types of valve construction where the disk travels in a rotating or wiping motion over the face of the seat.

Road Building.—Almost every piece of machinery used in the building and maintenance of roads will operate more efficiently and economically when hard-faced. From the original excavation until the final smoothing off of the road during service, hard-faced equipment helps the contractor.

CHAPTER 15B

BRONZE SURFACING*

General, Applications, Bronze Weld Metals, Brazing Procedures, Finishing the Deposit.

General

In innumerable places in machinery of all types where there is relative motion between mating surfaces, provision must be made to reduce friction and wear to a minimum. This is accomplished (*a*) by providing proper lubrication, (*b*) by the use of ball and roller bearings and (*c*) by the use of non-ferrous, wear-resisting, low friction metals in rubbing contact with the usual cast iron or cast, rolled, forged or hardened steel surfaces. Most of the last-named bearings are made up of carefully machined or drawn bronze bushings and washers, cast babbit bearings, specially coated bronzes or special shapes manufactured by pressing and sintering from bronze powder.

Applications

In addition to the bronze bushings and specially shaped bronze bearings, there are many applications where it is difficult to machine properly and secure in place a bronze wear-resisting surface but relatively easy to apply a welded-on bronze surface. For example, a bronze-surfaced piston working against the cast iron or steel cylinder wall is very desirable and would suffer little wear itself and would occasion little wear on the cylinder wall. But, cut up as the periphery of the piston is by the ring grooves, it is impossible to make a strong, pressure-tight bond between a separately machined, thin bronze ring and the piston head. However, it is quite easy and relatively inexpensive *to coat the piston periphery with bronze by carbon arc, metal arc or oxyacetylene brazing methods and then machine to size.*

The flat faces of locomotive drive boxes, which take the pressure and rubbing wear from the inner surface of the drive wheel hubs, provide another illustration of the desirability of welding a wear-resisting bronze surface to the cast steel drive box.[1]

Brazed-on wear-resisting bronze pads on machine tools; non-galling bronze pads on door dogs; corrosion-resisting, non-scoring bronze valve seats; non-scoring bronze pressure edges in deep drawing dies; the building

* Prepared by committee consisting of I. T. Hook, The American Brass Co., *Chairman;* C. E. MacQuigg, Ohio State University; J. R. Dawson, Union Carbide and Carbon Research Labs.

up of worn surfaces in all types of machinery and filling holes for rethreading illustrate a few of the many applications.

Bronze Weld Metals

Several types of bronze are in common use for the placing of wear-resisting surfaces. They are applicable in some cases by the oxyacetylene torch and in others by the carbon arc or the metal arc. These several bronzes are listed in Table 1. The common names are given in the caption for each group.

Table 1

Group No.	Approximate Composition, %	Approximate Flow Point, °F.	Approximate Brinell Hardness of Deposited Metal[3]	Remarks
1.	Naval brass. High zinc bronze, Tobin bronze, Chamet bronze, Bridgeport bronze, Roman bronze:			
	0.5 to 1.5 Tin 37 to 43 Zinc Remainder, Copper	1595 to 1625	68 to 72	Applicable by the oxyacetylene torch only
2.	Manganese Bronze:			
	0.75 to 2.0 Tin 0.75 to 1.5 Iron 0.05 to 0.5 Manganese 0.00 to 0.15 Silicon 38 to 43 Zinc 0 to 10 Nickel Remainder, Copper	1595 to 1625	74 to 101	Applicable by the oxyacetylene torch only. A harder, more wear-resisting bronze than that of Group 1
3.	Phosphor bronze, Tin bronze:			
	8 to 12 Tin 0.10 to 0.50 Phosphorus Remainder, Copper	1830 to 1900	85 to 93	Applicable by the carbon arc or, as covered electrodes, by the metal arc. Excellent wear resistance against steel or cast iron
4.	Copper silicon alloys:			
	2.5 to 4 Silicon 0 to 1.25 Manganese 0 to 2 Zinc 0 to 2 Tin 0 to 2.5 Iron	1866 to 1930	69 to 76	Applicable by the carbon arc or, as bare or covered electrodes, by the metal arc
5.	Aluminum bronze:			
	5 to 14.5 Aluminum 0 to 4.5 Iron Remainder, Copper	1904 to 1940	112 to 210	Applicable by carbon arc or, as covered electrodes, by the metal arc. A non-scaling deposit for valve seats, etc.

The Groups 1 and 2 applicable by the oxyacetylene method, make a free flowing deposit on cast iron, steel, high copper or nickel alloys which can be built up to any desired thickness. The coatings made by Group 2 alloys are usually harder than those made by Group 1 alloys. Hence, in

applications in which wear resistance is important as on the rubbing surface of piston heads, the Group 2 alloys should always be used.

The phosphor bronzes of Group 3 also offer excellent wear resistance.[2] The hardness increases with the tin content but if the tin is higher than 10.5%, the filler rods are obtainable in cast form only. Bennett[1] mentions the use of a leaded tin bronze (85 copper, 10 tin, 5 lead). Such leaded bronzes, obtainable in cast form only, suffer more wear themselves but occasion less wear on the steel or cast-iron mating surface.

The manganese bronzes, Group 2, or the phosphor bronzes, Group 3, would ordinarily be preferred to the copper silicon alloys of Group 4. However, the ease with which the latter alloys can be applied by a short carbon arc or as bare or covered metal arc electrodes has occasioned their use for surfaces which are desired primarily for moderate wear resistance.[1]

The aluminum bronzes are quite as hard and wear resisting as the manganese or phosphor bronzes. Moreover, they retain their hardness, and nonscaling qualities at reasonably high temperatures, 400 to 700°F. As seats for exhaust ports of high-duty internal combustion engines, aluminum bronze resists the valve pounding, gas scaling and scoring action unusually well. Though commonly applied as inserted seats, the aluminum bronze may also be applied by the carbon arc to build up worn seats. Covered metal arc electrodes are also available.

The Brinell hardnesses given are for the metal in the as-deposited condition. All of them can be hardened still further by cold peening, rolling or burnishing.

Brazing Procedures

One important point in applying these wear-resisting facings is that, when the bronze is being applied to cast iron or steel, *care must be exercised to avoid melting the base metal.* If the cast-iron or steel base metal is fused, globules will float up into the facing bronze defeating in a large measure the purpose of the latter. Such particles of fused ferrous metal are usually harder than the bronze and make points in the surfacing which cause high wear and possible scoring in the mating surface.

It is a simple matter to braze the metals of Groups 1 and 2 to a ferrous base metal with the oxyacetylene torch without danger of fusing the base metal. With the carbon or metallic arc used with Groups 3, 4 and 5 care must be exercised to keep the lower end of the arc on the pool of bronze. With a reasonable black preheat in the base metal, sufficient heat will be transferred through the pool of molten bronze to secure a strong surface-alloyed bond of bronze to base metal without its being necessary to melt the latter. In applying a bronze coating to a heavy cast or wrought steel section, local overheating should be avoided as it promotes intergranular penetration of the bronze into the base metal. A good black preheat will minimize this tendency. Cast iron is not ordinarily subject to intergranular penetration but a good preheat with a lower welding heat may reduce the liklihood of fusing the base metal.

In preparing the base metal for surfacing, all scale, oil and graphite should, as far as possible, be removed. The surface should then be *fluxed* to avoid its being oxidized in the heating-up period. The usual brazing

fluxes will be satisfactory for the facing alloys of Groups 1, 2 and 3. For alloys of Groups 4 and 5, a liberal addition of sodium fluoride, potassium acid fluoride or lithium fluoride should be made to the brazing flux. When welding with rods coated with such fluxes, the operator should do the work in a well-ventilated place and avoid breathing the welding fumes.

Finishing the Deposit

The deposit may be made as thick as is desired and machined in the usual manner. If more than $^3/_{16}$ in. of surfacing is desired, it should be run in two or more passes. Usually the deposit will be sufficiently hard in the as-welded condition. It may, however, be hardened by cold peening or cold rolling when this is considered advisable. In the case of valve seats, the increased hardness by cold working will be beneficial. The work-hardened facing metal will, for example, stand up better under the pounding of poppet valves. The methods described above are applicable not only for the building up of worn or damaged surfaces and to reduce wear but are equally applicable for the fabrication of new parts having a particular service as was noted above in the paragraph on "application."

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CHAPTER 15C

METAL SPRAYING*

Process, Properties of Sprayed Metal, the Operation of the Process, Typical Applications of Sprayed Metal.

PROCESS

THE metal spraying process—or metallizing as it is frequently called—employs a hand tool or gun of the self-contained portable type. With this one unit, metal is melted and projected simultaneously. Most metal spray guns require that the metal be supplied in wire form; although dust or powder guns are in wide use at this time which spray aluminum and zinc dust, as well as other soft metals.

This wire or powder is automatically fed through the gun, at a uniform speed, into an oxygen-gas flame. The flame immediately and continuously melts the end of the wire as it emerges from the wire nozzle. A powerful jet of compressed air atomizes the molten metal and blows it out of the nozzle of the gun in a fine, dense spray. Upon reaching the surface to be metallized, the tiny particles of sprayed metal chill almost instantly and key themselves into the base metal or other base material. This simple method of applying metal coatings has found increasingly wide use in recent years, particularly since the introduction in 1935 of high-speed, heavy-duty guns using $^1/_8$-in. wires.

Equipment

Figure 1 shows the basic equipment necessary to do metal spray work. A compressed air supply of approximately 30 cu. ft. per min. is required. Where the climate is excessively damp an air-drying unit is recommended to eliminate excessive moisture in the air supply. In dry climates a small air filter is sufficient. Air, fuel gas and oxygen regulators control the supply of these items which are supplied to the gun through rubber hoses. The wire, on spools or in coils, is fed from the turntable-type reel stand.

In operation the air, fuel gas and oxygen pressures are set at the regulators. The wire is fed between two knurled rolls in the gun. These rods are driven by a small air turbine, geared down by reduction gears. The speed of the wire is controlled either by a needle valve regulating the sup-

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ply of air to the turbine or, on the latest type guns, a power absorption governor.

Metal spray guns and accessory equipment have been improved radically during the past six years and now are extremely reliable in operation, allowing the use of multiple gun set-ups for production purposes. Spraying speeds have been increased and spraying costs reduced. The guns most recently developed handle any size wire from 24 B&S gage to $^1/_8$ in., depending upon the spraying capacity required. These guns will operate on a number of different heating gases simply by changing the type of wire nozzle.

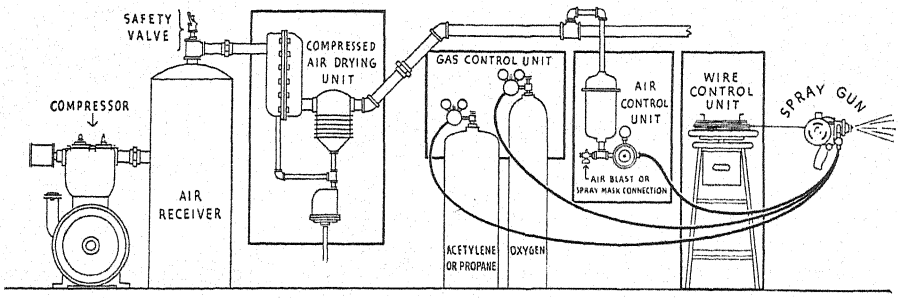


Fig. 1—A Typical Metallizing Installation, Showing the Basic Equipment Necessary to Do Metal Spray Work

Range

The metal spraying process makes it practical to secure, at low cost, surfaces with the desirable qualities of any of the more expensive metals, while using the cheaper material to support that surface. A unique feature of metallizing is that one section of a surface can be coated with one particular metal and other parts of the same surface with different metals. Alternate layers of as many dissimilar metals as desired can be applied, one on top of the other. Non-ferrous metals can be applied to ferrous metals and vice versa.

Sprayed metal can be placed, where wanted and as wanted, up to any thickness required. Metals with high melting temperatures may be sprayed successfully on those having low melting temperatures. This is true whether the metal with the lower melting point is a previously applied coating or not. Even wood, fabrics or paper can be metallized without charring if proper precautions are taken.

Parts of any size or shape can be metal sprayed, regardless of location. Applications may be made before, during or after fabrication of the part—either in the shop or in the field. Metal spraying uses no pigments, solvents, fluxes or other vehicles. Commercial metal wire is the only raw material employed aside from oxygen, fuel gas and compressed air. No preheating of the base is necessary, and there is no danger of warping or distorting the piece to be sprayed.* While the process has fields of its

* In certain cases preheating may make possible the securing of a bond. Care must also be exercised in certain instances as, for example, spraying aluminum on $^1/_8$-in. chrome-molybdenum steel.

own for building up worn or mis-machined parts and for providing corrosion-resistant coatings, it also can be used to advantage as an adjunct in plating or coating processes.

Sprayed metal may be applied in practically any desired thickness on any base material—metallic, fibrous, vitreous, conducting, insulating or inflammable. Economical and practical operating considerations, however, usually determine the actual thickness.

Wires

Any commercial metal obtainable in wire form can be sprayed. Those wires used most commonly are:

Aluminum	Copper	Steel, Low Carbon
Babbitt	Iron, Ingot	Steel, Medium Carbon
Brass	Lead	Steel, High Carbon
Bronze, Aluminum	Lead, Antimonial	Steel, Stainless
Bronze, Commercial	Lead, Tellurium	Steel, Chromium
Bronze, Manganese	Monel	Steel, Manganese
Bronze, Phosphor	Nichrome	Steel, Nickel
Bronze, Tobin	Nickel	Tin
Cadmium	Nickel Silver	Zinc

For satisfactory results wires must be uniform in quality, chemical analysis, temper and diameter. A number of special analysis wires processed specifically for metallizing have been developed and are available under various trade names. Advice on the application of these wires may be obtained from the manufacturers.

Gases

Acetylene, propane, manufactured gas, natural gas and hydrogen are the fuel gases used for metal spray work. While spraying costs are the principal factor in determining *which* gas should be employed, there are other important factors to consider. Hydrogen is too expensive unless obtainable as a by-product. Natural gas, although not generally available, is economical to use and gives excellent results on all types of work, particularly if the Btu. value is high. Manufactured gas, because of its low Btu. value, is used principally for spraying the lower melting point metals and small gage wires. It offers also the additional advantage of low cost.

Acetylene is by far the most widely used gas, although during the past few years propane has come into extensive use. Both of these gases are available practically everywhere. They can be transported easily to jobs in the field and their use requires no piping, booster compressors or other extra equipment. While the cost per cubic foot is lower for propane than acetylene, propane requires more oxygen for proper combustion. Because of this, the total gas costs per pound of metal sprayed are about equal. Therefore local prices determine which gas is the more economical.

Acetylene gas has the following advantages: a cleaner flame giving less dust; more uniform coatings; better atomization and coating structure with 11 B&S or $^1/_8$-in. nickel, monel, stainless steels and other chrome-nickel alloys; higher hardness yet retention of machinability with carbon steels. Nevertheless, acetylene has the disadvantage of offering operating pressure limitations, which in some cases cause reduced production speeds.

Propane gas has the following advantages: no pressure restrictions; good flame stability, making it easier to light and operate without backfires; a stable flame at the very low pressures used with fine gage wires. However, it has the disadvantages of slightly more dust, greater variation in coating results, lower hardness of carbon steel coatings and poor atomization and structure of 11 B&S or $^1/_8$-in. nickel, monel, stainless steels and other chrome-nickel alloys.

Spraying Speeds

Improvement in the design and construction of metallizing equipment and the use of larger size wires have combined to increase spraying speeds greatly and to reduce operating costs. Operating costs vary widely, depending upon the nature of the work and local conditions, but the following table will indicate the high spraying speeds obtainable with modern metal spray guns.

Metal	Pounds per Hour*	Metal	Pounds per Hour*
Aluminum	7.2– 7.7	Nickel	9.0– 9.9
Brass	20.0–24.6	Stainless steel	9.8–11.6
Bronze	17.5–25.4	Low carbon steel	10.6–11.2
Copper	16.5–17.9	Medium carbon steel	10.0–11.0
Iron	10.6–11.2	High carbon steel	10.0–11.4
Lead	44.3–107.0	Tin	28.7–64.0
Monel metal	11.2–11.6	Zinc	24.7–30.2

* Dependent upon gas and gas pressures used.

PROPERTIES OF SPRAYED METAL

Physical Properties

Photomicrographs of sprayed metal show that it is made up of a multiplicity of tiny particles which, by high velocity impact on a surface when in a molten or plastic state, are flattened out and interlocked by partial fusion. Typical stratified layers may be observed.

The fine grain of the sprayed metal influences both the cohesion between particles and the adhesion of the particles to the surface on which they are sprayed. Small particles join to each other better and penetrate more easily into the pores of the surface than coarser ones. The probability of merely bridging the pores is less when using a fine spray. Therefore, it is extremely important that the spray gun be kept adjusted correctly and that proper technique be employed at all times.

While the physical properties of the original metal might still be present within each individual particle of sprayed metal, the tensile strength, ductility and elongation of sprayed metal as a whole are governed by its physical make-up. Stratified structure, presence of oxides, absorbed gases and voids between the particles—all these are deciding factors which outweigh the physical properties of the metal wire before it is sprayed.

In so far as tensile strength, ductility and elongation are concerned, it is best not to depend on them when considering the use of sprayed metal.

For example, the tensile strength of sprayed 18–8 stainless steel will be from 10,000 to 14,000 psi., while the ductility and elongation will be practically nil. In other physical characteristics, however, such as hardness, compressive strength, wear resistance, corrosion resistance and heat and electrical conductivity, the properties of the original wire, although modified, still exist. In the case of wear resistance the qualities are often improved to a considerable extent.

Porosity

Due to the stratified structure of sprayed metal, it necessarily possesses a certain perviousness. Hence, there is always the possibility of gradual permeation, more or less, through the complicated network of voids between individual particles. If such penetration takes place under conditions favoring electrolytic action between base and sprayed metal—or to be more specific, if the sprayed metal is cathodic to the base, the effect is likely to be the breaking of the bond and the separation of the sprayed metal from the base. In such cases it is essential that the natural permeability of the sprayed coating be counteracted, especially if the coating is to provide protection against corrosion, by one or more of the following methods:

1. The application of successive coatings which will seal up gradually, as layer after layer is applied, any pores which might prevail in each preceding coating.
2. The treatment of the coating with some material or chemical solution which will serve to seal the pores physically.
3. The mechanical working of the surface of the metal coating. Lead and tin coatings, for instance, can be sealed by a thorough wire brushing since they are relatively soft.

In the case of zinc and aluminum, which are anodic to iron, the permeability of the coating is not a factor. Any interstices existing in the sprayed coating are, under most circumstances, quickly and effectively sealed by the corrosion-product of the sprayed metal itself.

Advantages of Porosity

The permeability of sprayed metal is a definite advantage when the coating is applied as a bearing surface, because lubricants are absorbed by, and retained in, the minute pores of the coating. This is one of the reasons for the extremely long service-life of sprayed bearing surfaces. Such surfaces frequently outlast the original many times over.

Appearance of Sprayed Metal

Sprayed metal has a matte or "sanded" surface appearance. The natural metallic luster does not appear until the coating has been finished by wire brushing, machining or grinding. The "color" of the applied metal may change slightly during the spraying operation. Thus, although the sprayed metal may be of the same analysis as the base material, it seldom will be a perfect match in tone.

THE OPERATION OF THE PROCESS

Surface Preparation

Sprayed metal is neither welded nor brazed to the base metal. The bond between the sprayed metal and the base is purely mechanical. Therefore, the proper preparation of the base before the application of the coating is an essential and extremely important step in the process. Re-

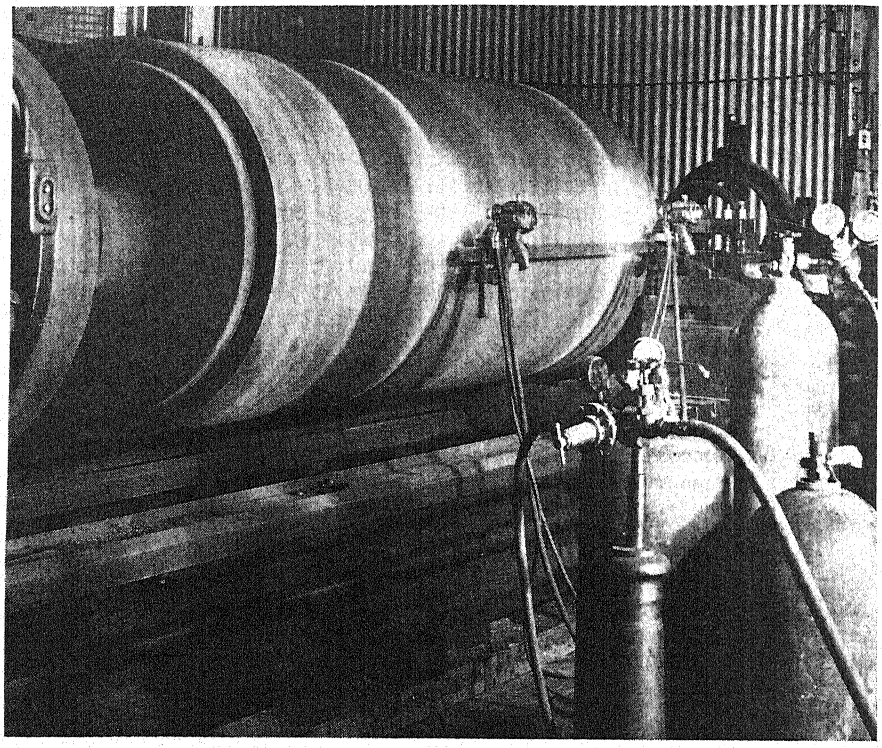


Fig. 2—Cast-Iron Dryer Roll, 42 In. in Diameter by 100 In. Long, Is Made Resistant to Corrosion by the Application of $^{3}/_{32}$-In. Sprayed Stainless Steel. Two Metallizing Guns Were Employed Simultaneously to Reduce Spraying Time

gardless of the method used, preparation of the base material should produce a multiplicity of minute keys or locks for holding the sprayed molten metal firmly to the surface. It is also highly important that the prepared surface be absolutely clean and free of all contamination, particularly oil and moisture.

For large flat areas, the surface is prepared by blasting with sand or steel grit. The grit blasting operation develops keys or dovetails which anchor the coating securely to the base metal.

Machine elements which can be mounted in a lathe, such as bearing surfaces, pump plungers and rolls, can be prepared by rough-threading or by the use of a shaft-preparing tool mounted in the tool post of the

lathe. Rough-threading, if properly done, provides a satisfactory surface for metallizing on practically all steel shafts. It is not satisfactory, however, on bronze, brass or steels containing nickel. The shaft-preparing tool provides a satisfactorily prepared surface on any metals which can be machined and affords the strongest mechanical bond over keyways and broken surfaces.

Sprayed metal should be applied as soon as possible after the surface is prepared in order to avoid corrosion of the roughened areas. In no case should more than eight hours elapse between preparing and metal spraying. If handling of prepared surfaces is necessary, it should be done with clean cotton gloves so that the surfaces are kept free from grease, oil, moisture and dirt.

Surfaces of open-grain structure, such as unglazed pottery, terra-cotta, brick, plaster, wood, paper and cloth do not require preparation before metal spraying. It is only necessary that they be clean and dry. Sprayed metal can be applied firmly to glass and other ceramics if they are heated to the correct temperature before the metal is applied.

Spraying Technique

In all metallizing work it is generally recommended that the metal be applied in a series of light coats. While extremely heavy coats can be obtained with one pass of the gun, such procedure is apt to result in stratification of the coating. The gun should be held from 4 in. to 10 in. from the work, depending upon the metal being sprayed. In order to insure highest spraying speeds, lowest costs and completely uniform results, gas pressures should be adjusted to obtain the correct flame.

When spraying shafts, the gun is mounted in the tool post of the lathe. If 2 in. in diameter or less, the shaft should be turned at a number of revolutions which will give a surface speed of approximately 35 ft. per minute, and the carriage feed should be set at $^1/_8$ in. per revolution. If the shaft is over 2 in. in diameter, the surface speed should be approximately 50 ft. per minute. In such instances the carriage feed should be $^1/_6$ in. per revolution.

Since practically all flat surfaces are sprayed by hand, a certain amount of skill is required by the operator if an even coating is to be obtained. Generally speaking, it is advisable to first calculate the weight of metal required per square foot of surface. After measuring the entire area, or merely a section of the area to be coated, the exact amount of metal required should be weighed out. Then the operator simply applies this metal, as evenly as possible, in a number of crisscrossed coats.

Small metal parts such as pipe fittings, pole hardware and similar items, which cannot be economically coated by hand, can be sprayed in a tumbling barrel. This method of mass spraying small parts is effective and economical.

Finishing Sprayed Metal

Sprayed metal, properly applied, may be polished, ground, turned, filed or otherwise finished in a manner quite similar to that ordinarily employed on cast or forged metal. However, if the best results in machining sprayed

metal are to be obtained, the unusual structure and properties of sprayed metal make it necessary to disregard the usual machine shop practice for grinding and setting the tool. A good general rule is to set the tool above the center sufficiently to reduce front clearance, or working relief angle, to a minimum. This is especially advisable for the finish cut.

A grinding wheel suitable for a given metal in rolled form will often be unsuitable for the same metal in sprayed form. For this reason, some experimental work with various grades of wheels may be required to obtain the best results.

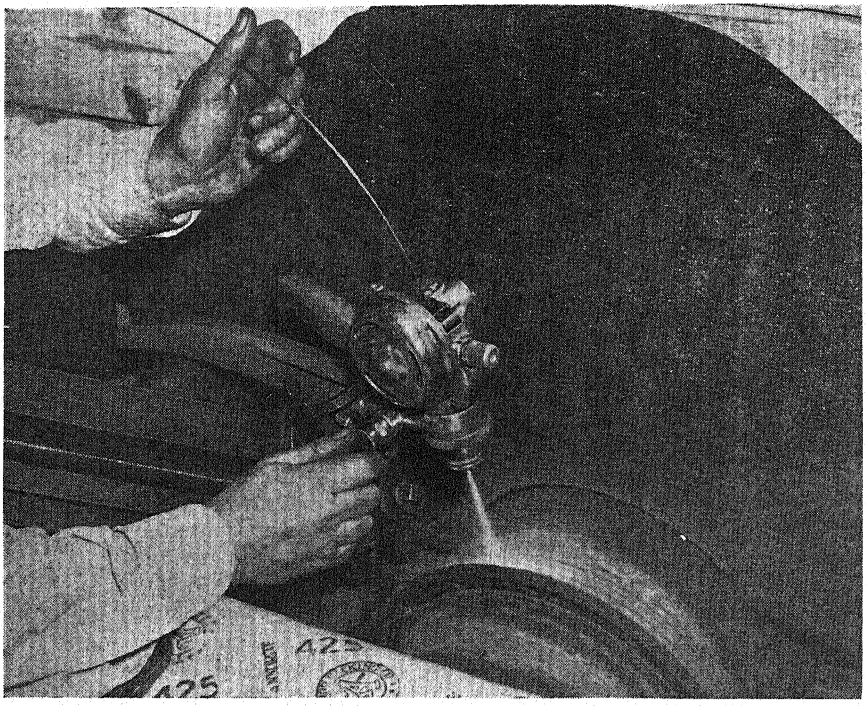


Fig. 3—Prepared Shaft Being Built Up by Spraying with Stainless Steel

Complete information on the recommended procedures, setting of tools, speeds and feeds for machining, as well as grinding wheel recommendations for both dry and wet grinding of all the sprayed metals, is available from the manufacturers of metallizing equipment. If these instructions are followed, no difficulties will be encountered in obtaining high speeds and low costs for the finishing operations.

When polishing metal which has been sprayed on a non-metallic base such as wood, plaster or cement, care must be exercised to avoid overheating since this may tend to expand and buckle the sprayed metal and seriously affect the bond between the two materials.

The original matte finish of sprayed metal is much more economically adapted to wire-brushed or scratch-brushed effects than highly polished

finishes. On decorative work, emery cloth or steel wool is frequently used to "highlight" and polish the high points, thus making it easy to secure attractive contrasts at low cost. To obtain a ground or draw-file finish, abrasive cloths of from 50 to 100 grit size are suitable.

To retain the original color, decorative sprayed metal surfaces should be protected by lacquering. Bronzes are often oxidized with liver of sulphur (an impure potassium sulphide in liquid form) or other agents. One part of liver of sulphur mixed with about thirty parts of water develops a statuary bronze finish. It is applied with an air brush and when the desired shade is obtained, the part is washed thoroughly with cold water to stop oxidation. Then the piece is rubbed with wire brush or steel wool to "highlight" it. Where antique-verde finish is desired, sprayed lead is used as an undercoat. In all cases, after proper effects are secured, the part is sprayed with lacquer to preserve the finish.

General Precautions

For blast cleaning and metal spraying in confined spaces, good ventilation must be provided—either by a forced draft arrangement or by means of a pressure ventilated helmet or both. Special precautions should be taken when spraying cadmium or lead, both of which are toxic. All industrial regulations pertaining to the safe use of these metals should be adhered to rigidly. Respirators and special clothing are demanded for certain work.

TYPICAL APPLICATIONS OF SPRAYED METAL

Applications

The principal applications for sprayed metal are for:

1. Altering shapes or adding dimensions or weight to worn surfaces of bearings and mis-machined (undersized) parts.
2. Applying superior, high cost metals to low cost base metals in tool and equipment manufacture, in order to obtain corrosion resistance or longer wear-life.
3. Providing protection against atmospheric corrosion.
4. Providing protection against corrosive liquids.
5. Providing protection against high temperatures.
6. Repairing defects (blow-holes, sand holes, gas holes, porosity) in iron, steel, bronze, aluminum, magnesium and other castings.
7. Obtaining electrical contacts, and forming coatings of desired conductivity or resistivity, on metallic and non-metallic materials.
8. Providing protection against erosion and cavitation.
9. Obtaining reflecting surfaces or mechanical joints on glass.
10. Producing accurate replicas by use of separable deposits.
11. Balancing equipment for high speed rotation.

Applications of the metallizing process, as already indicated, can be divided into two main classifications: *mechanical*, which embraces all those having to do with the salvage, maintenance or manufacture of mechanical equipment; and *corrosion resistance*, which covers all those pertaining to the checking of atmospheric or chemical deterioration of metal products. Two sub-classifications are: *electrical*, having to do with the application of metal to carbon, graphite, porcelain and other non-

metallics, and to various dielectric materials for localized inductive areas; and *decorative*, which concerns a field as yet undeveloped and about which little of real practical value is known.

By far the most varied and practical field for metallizing is the *mechanical:* present-day equipment, designed for heavy duty high-speed performance, has increased considerably the scope for metal spraying in this field. Reduced spraying costs, too, have been an important factor in the wide use of metallizing for mechanical equipment. Thus, the point has been reached where the salvage and maintenance applications of even a few months age are standard production procedure in the plants of many manufacturers today. The ease and economy of applying stainless steel to a thickness of $^{3}/_{32}$ in. on the radius to huge rolls (Fig. 2), for instance, have indicated just what is being done along these lines.

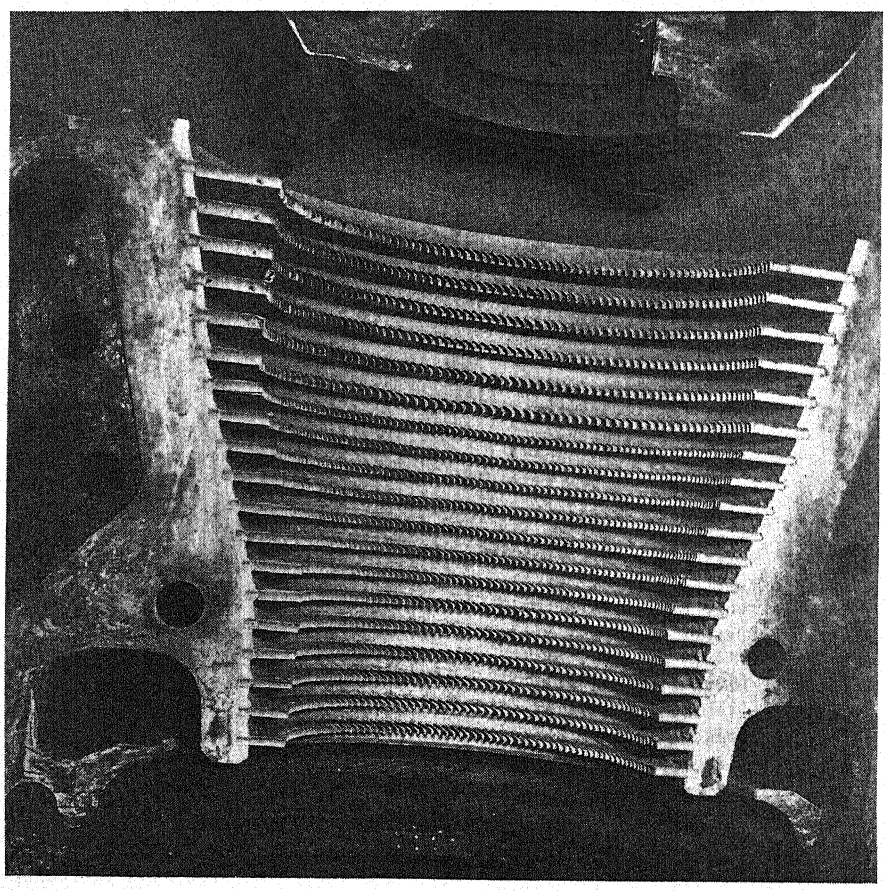


Fig. 4—The Lower Half of a Turbine Casing, Metallized with Stainless Steel to a Thickness of .020 In. to .030 In. After It Had Been Completely Grit-Blasted and Prepared for Metallizing

Figure 3 illustrates the facility with which repairs can be effected *in situ* to large turbine shafts, thus saving the very costly procedure of complete disassembly. Crankshafts are metallized in large quantities, as a maintenance procedure, eliminating the expensive procedure of periodically grinding undersize which, in turn, necessitates the use of many off-standard bearings. The metallizing process is particularly applicable to very large steam and Diesel engine crankshafts. Years of service under all types of severe operating conditions indicate, beyond doubt, that the sprayed metal on these crankshafts will outlast the original.

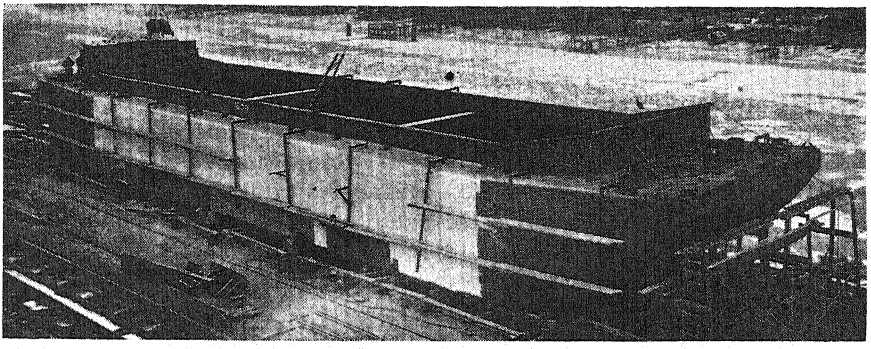


Fig. 5—Welded Steel Coal Barge Sprayed Inside and Outside with Zinc 0.010 In. to Protect the Hull from Corrosion

The elimination of erosion and the repair of eroded surfaces are common practice, particularly on steam turbine cylinders such as illustrated in Fig. 4. Erosion takes place at the base of the stationary blades and in time lowers the efficiency of the turbine to a point where repairs or replacement are necessary. Stainless steel applied to new cylinders will prevent the erosion, and in the case of units that have been in service, further erosion can be prevented and the cylinders restored partially if not entirely. Repairing of cavitated water wheel runners is another application of especial value, and one that has withstood the test of time under varied conditions.

Corrosion-resistant applications involve mainly the use of "white metals" such as zinc, tin and aluminum. These cover a wide and varied range. Commercial refrigeration equipment, water towers and tanks, filter beds, railroad bridges, structural steel, glycerine tanks, canal gates and steel barges are representative of many (Fig. 5).

Another branch of the corrosion-resistant group is that which is designed to prolong the life of equipment subjected to high temperatures. Furnace parts, melting pots, crucibles, ladles, salt pots, annealing boxes and similar equipment have been treated successfully, resulting in an increase in service-life of from 150 to 500%.

In conclusion it should be remembered that the metallizing process, in spite of its many and varied uses, has its limitations. However, all these limitations have been clearly defined after years of trial and error. Now, abundant data are available on the process, and dependable specifications on surface preparation, application and technique have been formulated for every tried and proved application.

CHAPTER 15D

FLAME HARDENING, SOFTENING AND STRENGTHENING*

Flame Hardening: Development of the Process, Field of Application, Furnace Hardening vs. Flame Hardening, Choice of Materials, Physical Properties of Flame-Hardened Steels, Flame-Hardening Procedure, Flame Hardening Cylindrical Surfaces, Flame Hardening Irregular Surfaces, Heat Treatment. Flame Softening: General Requirement for Flame Softening, Flame-Softening Procedures, Typical Results. Flame Strengthening.

FLAME HARDENING

THE term Flame Hardening encompasses the use of the oxyacetylene flame to produce a temperature in a ferrous material such that subsequent quenching with suitable media, generally water or compressed air, will increase its hardness. The process of flame hardening is entirely analogous to furnace heat treatment wherein steels and certain cast irons are hardened by heating above the A_3 transformation or critical point (1275–1650°F.), depending on the carbon content, at which point the solid solution of carbon in γ-iron (austenite) is formed. Quenching from this temperature causes a change in the iron crystal to the α-form in which carbon is only slightly soluble. The carbon dissolved in the austenite crystal is precipitated in the form of iron and other metal carbides producing crystal structures of considerable hardness.

Since the flame-hardening process has been applied largely to hardening thin surface layers of thicker sections, it has been loosely termed local or surface hardening, and has been confused with the carburizing process of case hardening and with nitriding. Flame hardening employs the oxyacetylene flame merely as a heating medium in an operation analogous to furnace hardening, and involves no change in the chemical composition of the material such as the introduction of carbon or nitrogen into the surface layers of the material as in case hardening. The standard furnace heat-treating operations of hardening, normalizing, annealing and tempering can be localized to

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shallow surface layers by using the rapid heating effect of the oxyacetylene flame.

Development of the Process

Development of the process was hindered at the outset by the general lack of suitable water-cooled apparatus, capable of maintaining broad areas of stable oxyacetylene flames in close contact with heated metal so that only limited use was made of the heat of single oxyacetylene flames for treating restricted surface areas. The introduction of rail end hardening to reduce rail joint maintenance in 1927 and the subsequent widespread adoption of this process as a routine maintenance operation by many railroads marked the first large-scale application of flame hardening and focused attention on the development of apparatus suitable for industrial use. During the past decade, flame hardening of the teeth of large gears has gradually become a standard operation, and an active development of the process to include the hardening of common wearing surfaces such as cams, guides, coupling boxes, pulley sheaves, roll wobblers, ball and roller races, crankshaft journals, pistons, cylinder liners, etc., is in progress.

Field of Application

The flame-hardening process is particularly suited to the hardening of small contact areas on large sections which could not previously be hardened by the furnace method because of the *size of the object* and resulting distortion. The use of expensive liners, bushings or raceways can frequently be avoided by heating and flame hardening the contact surfaces only, leaving the remainder of the object undistorted. The bearing surfaces of large gear teeth and roller or ball races are examples of this field of application. Smaller objects can also be flame hardened economically when they do not amount to a sufficient volume to warrant lighting a furnace for furnace treatment. In this case, the flame-hardening process can be regarded as an auxiliary to the furnace hardening method, the choice between processes depending on the volume of work to be done. In many shops where there is occasional need for hardening, but where the volume of work is not sufficient to warrant construction of a hardening furnace, flame hardening finds application.

The flame-hardening process is extremely flexible as regards the size and shape of work that can be hardened with relatively simple portable equipment. The time required to flame harden is generally only a fraction of that required for the furnace method, and since the hardening is done on finished surfaces, considerable savings in machining and regrinding costs are possible.

Furnace Hardening vs. Flame Hardening

The main difference between the furnace- and flame-hardening processes is that in the former the entire object must be brought to hardening temperature, whereas in the latter, only a thin surface layer $^1/_8$ to $^1/_4$ in. in thickness is so heated. To obtain high degrees of hardness with the furnace method, very drastic quenches must be used because of the annealing

effect of the heat in the center of the object treated, which frequently results in breakage or distortion due to internal quenching strain. In flame hardening, because of the rapid rate of heating and the sharp temperature gradient between surface and interior of the object, a substantial self-quenching effect is obtained which is frequently sufficient to produce the desired surface hardness by air cooling.

In furnace hardening, tedious and exact heating and quenching procedures must be followed to prevent loss of ductility and impact resistance of the core. To obtain the desired surface hardness and the desired physical properties in the core, the more expensive alloy steels must frequently be used. In flame hardening, the core need not be heated high enough to impair its physical properties, a high degree of surface hardness is obtained, resulting in a less complicated hardening technique, and offering the possibility of using the cheaper plain carbon steels. Distortional effects occur in flame hardening only when one surface of a thin flat object is heated and quenched. The object tends to shorten on the hardened side. This distortion can be reduced by partially immersing the object in water, or can be compensated for by prebending in the reverse direction before hardening. In the case of circular sections or where both sides of a flat object are hardened simultaneously, as with gear teeth, distortion is practically nil.

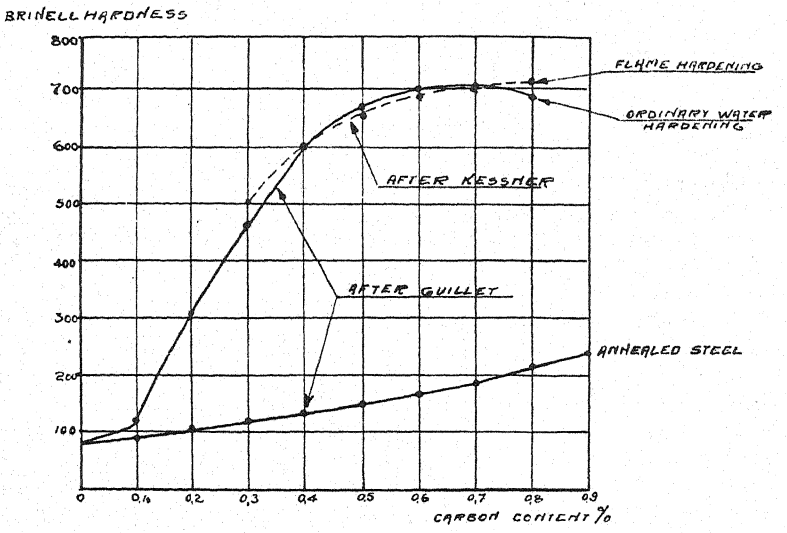


Fig. 1—Effect of Carbon in Producing Hardness After Heat Treatment

Choice of Materials

Plain carbon steels can be successfully hardened when the carbon content is above 0.35%, best results being in the 0.35–0.70% range with water the usual quenching medium. Above 0.70% carbon, care must be used in quenching to avoid surface checking, particularly with the progressive method of hardening; milder quenching media—compressed air or

compressed air-water mixtures—are frequently used. A hardness of 400–700 Brinell is obtainable depending on the severity of the quench.

The standard S.A.E. steels can be flame hardened with carbon as low as 0.35%. In general, the low alloy steels are particularly suited to flame hardening, because of their low critical quenching rate. Many of the higher alloy steels, such as the 13% chromium steels, have been hardened with carbon as low as 0.15%.

Figure 1 illustrates the effect of carbon in producing hardness *after heat treatment.*

Physical Properties of Flame-Hardened Steels

Tables 1 to 5 illustrate some of the types of steels which have been successfully flame hardened, with some data on the metallographic and physical properties obtainable by flame hardening. Table 1 indicates some of the S.A.E. steels which can be readily flame hardened. Tables 2 and 3 contain observed data relative to the surface hardness produced on representative steels and cast irons, using water or compressed air quenches. Since these data were taken under varying conditions of heating and quenching in shop practice on objects of various sizes and shapes, they do not represent the maximum hardness obtainable for the various analyses. Table 4 illustrates the physical properties obtainable in flame-hardened surfaces. Table 5 indicates the typical crystal structure produced by flame hardening at varying depths below the surface of the object. A very gradual transition in hardness from the martensitic surface to the pearlitic core is obtained in flame hardening.

Table 1—Steels Which Can Be Successfully Flame Hardened

Series	C	Mn	Cr	Ni	Mo	Va	Si
S.A.E. 1000	0.35–0.60	0.60–0.90	...	...	...	...	...
S.A.E. 1300	0.25–0.40	1.60–1.90	...	...	...	...	...
S.A.E. 3100	0.25–0.40	0.50–0.90	0.45–0.75	1.00–1.50	...	...	...
S.A.E. 3200	0.25–0.40	0.30–0.60	0.90–1.75	1.50–2.00	...	...	...
S.A.E. 3300	0.25–0.40	0.30–0.60	1.25–1.75	3.25–3.75	...	...	...
S.A.E. 4100	0.25–0.40	0.50–0.90	0.50–1.10	...	0.15–0.25	...	...
S.A.E. 4300	0.25–0.40	0.50–0.80	0.50–0.80	1.50–2.00	0.30–0.40	...	...
S.A.E. 5100	0.25–0.40	0.60–0.90	0.60–1.10	...	...	...	...
S.A.E. 6100	0.25–0.40	0.60–0.90	0.80–1.10	...	...	0.15 min.	...
Cromansil	0.25–0.40	1.00–1.20	0.40–0.60	...	...	...	0.80–1.00

Table 2—Observed Flame Hardness of Various Steels

Approximate S.A.E. Specification	C	Mn	P	S	Si	Cr	Ni	Mo	Va	Brinell Hardness Compressed Air Quench	Brinell Hardness Water Quench
..	0.35	1.45	..	..	..	...	..	..	..	...	500
1040	0.35	0.80	0.04	0.03	0.30	...	..	..	..	...	444
1045	0.45	0.75	0.04	0.05	..	...	..	..	..	...	555
1055	0.55	0.74	0.02	0.04	0.22	...	..	..	..	...	712
1095	1.00	0.30	0.02	0.02	..	...	..	..	..	...	700*
51210	0.12	Forging Rolled			..	13.00	..	..	..	444	...
51210	0.12	Stock			..	13.00	..	..	..	...	444
...	1.25	0.20	..	..	..	0.50	...	..	..	...	614*
3140	0.40	0.80	..	..	..	0.60	1.25	..	..	...	540
2330	0.30	0.68	0.02	0.03	..	...	3.48	..	..	...	600
								0.25	..	415	
4140	0.40	0.80	..	..	..	0.95	..	0.20	..	...	525
4140	0.40	0.80	..	..	..	0.95	..	0.20	..	375	...
	0.68	0.75	0.02	0.03	0.22	...	..	0.34	..	...	712
	0.90	..	..	..	..	...	..	..	0.25	...	725
6140	0.40	0.75	0.03	0.04	..	0.95	..	..	0.17	500	...

* Very mild quench by water.

Table 3—Observed Flame Hardness of Cast Irons

Type	Total C	Combined C	Si	Mn	P	S	Ni	Cr	Mo	Brinell Hardness Water Quench
Gray	3.46	0.76	1.58	0.76	0.144	0.083	..	...	..	540–600
Gray	3.44	0.69	1.51	0.87	0.194	0.087	..	...	..	550–610
Gray	3.44	0.77	1.70	0.75	0.300	0.085	..	...	..	550–615
Meehanite A	2.97	0.66	1.62	0.78	...	...	Nil	0.045	..	500–605
Meehanite C	3.04	0.68	1.65	0.79	...	...	Nil	0.045	..	500–620
Gray	3.22	0.65	1.73	0.75	0.212	0.089	..	...	0.47	560–635
Gray	3.15	0.70	2.00	0.90	...	...	1.37	...	..	525–575
Gray	3.30	0.73	1.34	..	...	...	1.43	...	0.85	550–605
Gray	3.19	0.84	1.22	..	...	...	1.11	0.10	0.76	550–605
Gray	2.87	0.84	1.87	..	...	...	0.18	0.21	..	560–610

If the cast iron has 0.35 per cent or more of its carbon in the combined state, it should be hardened in the same manner as steel but the hardness obtained will be less than that for steel with the same content of combined carbon. Malleable irons occur in two grades: so-called pearlitic malleable irons, with a matrix containing combined carbon in the form of pearlite and similar to steel, and fully malleablized iron with matrices of pure ferrite surrounding temper carbon. Pearlitic malleable irons harden similarly to steels of similar composition. Fully malleablized irons generally require pretreatment to dissolve some temper carbon into the ferrite matrix before they harden satisfactorily. With respect to malleable irons, many parts such as cam shafts, rocker arms, shifter forks, common to the automotive industry, are being successfully hardened in automatic production machines.

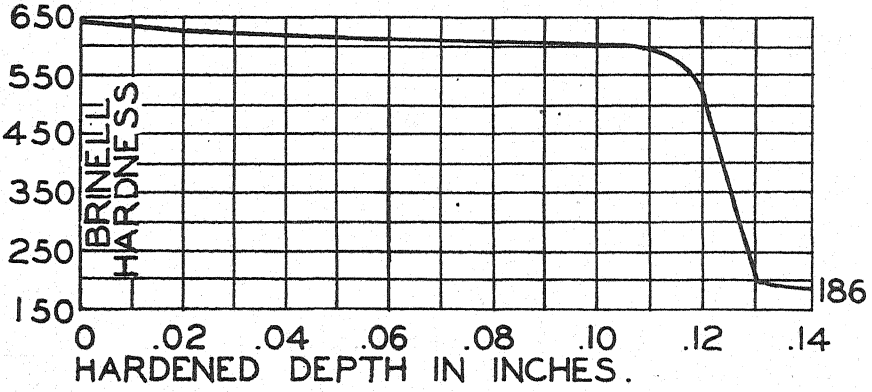


Fig. 2—Curve Giving the Variations of Brinell Hardness, According to the Hardened Depth, in the Case of a Gear Made of 0.5% Carbon Steel

Figure 2 indicates the relation of Brinell hardness and depth of case in a typical flame-hardened steel part.

Flame-Hardening Procedure

Flame hardening can be accomplished either manually or mechanically. Where limited areas of a part are to be treated, the area can be heated above the critical temperature by application of the standard welding torch, the entire area being brought to heat by manipulating the torch

back and forth across the surface. The torch is then removed and the surface quenched with water, or compressed air, or immersed in oil as required by the particular composition of the material. Extensive use is made of this process in hardening rail ends to reduce batter. An area the width of the running surface of the rail and some five inches in length is heated in less than two minutes with the welding torch to hardening temperature and then quenched with water. The volume of quench water is carefully regulated to give the desired hardness of 400 Brinell in a rail of 225 Brinell as rolled. The hardness thus produced resists the battering action of the car wheel at the rail joint which otherwise rapidly wears the rail section at this point.

In hardening extended areas such as the entire rail length, the hardening process is made continuous by incorporating both heating and quenching functions in the hardening tip, and providing means for moving the tip at a constant speed along the path to be hardened. Heating is accomplished by one or more rows of small oxyacetylene flames followed closely by a row of quenching holes. This method, known as progressive hardening, results in a more severe self-quenching effect than occurs where the entire surface to be hardened is simultaneously heated to the hardening temperature. A water quench unless carefully applied is therefore generally too severe for the higher carbon rail steels and compressed air or compressed air-water mixtures are used.

Table 4—Typical Composite Properties of Flame-Hardened Pretreated Steels

			Composition		
C	0.34	0.33	0.42	0.43	0.35
Mn	0.61	0.62	0.83	0.57	0.68
Cr	..	0.64	..	..	0.93
Ni	1.75	1.52	..	3.60	..
Mo	0.25	..	..	..	0.21
			Core Properties		
Tensile	185,000	130,000	105,000	135,000	130,000
Elastic limit	175,000	110,000	75,000	125,000	160,000
Izod	35	75	27	69	65
			Surface Hardness		
Brinell	555	534	514	578	627

Table 5—Hardness and Constitution of Flame-Hardened Surfaces

Type of Steel	Composition C	Mn	Ni	Cr	Mo	Brinell Hardness	Nature of Hardened Surface: Total Depth Affected, In.	Depth of Martensite	Depth of Troostite, etc.
S.A.E. 1050	0.46	0.69	..	..	..	615	0.130	0.078	0.052
S.A.E. 5140	0.42	0.71	..	1.05	..	615	0.108	0.084	0.024
Mn-Mo	0.39	1.59	..	..	0.31	610	0.111	0.092	0.019
S.A.E. 3230	0.29	0.56	1.52	1.16	..	610	0.108	0.080	0.028
S.A.E. 4340	0.36	0.60	..	1.13	0.31	592	0.108	0.096	0.012
S.A.E. 2340	0.36	0.70	3.34	0.20	..	585	0.123	0.086	0.037
Ni-Chromium-Mo	0.32	0.56	2.56	0.72	0.42	555	0.134	0.120	0.014

Figure 3 illustrates in schematic form the method of progressive hardening. The tip progressively heats the surface along the path of travel to hardening temperature and the quenching stream following imparts a uniform hardness to the area covered by the tip travel. Multi-flame tips must be water cooled to prevent overheating and flashback of the heating flames.

Tips 36 in. in width have been made for hardening wide areas, but where necessary to reduce the number of tips, narrower tips 3 in. in width and under can be used and wide surfaces hardened in successive strips. Auxiliary water jets are applied at the ends of the rows of heating holes to prevent flow of heat into the areas already hardened. The soft line between two successive passes can be held to narrow limits. The speed of tip travel will vary from 3 to 12 in. per minute, depending on the size and number of

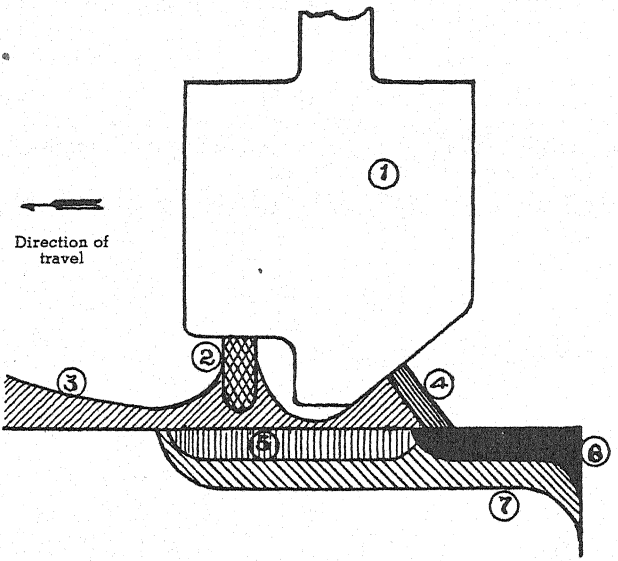


Fig. 3—(1) Torch; (2) Inner Cone; (3) Outer Flame; (4) Quenching Jet; (5) Metal Heated Above Critical Temperature; (6) Hardened Zone; (7) Annealed Zone

heating holes, and determines the penetration of the hardness. The degree of hardness obtained for a given steel analysis is regulated by the temperature to which the surface is heated and by the nature and volume of the quenching stream. To provide accurately controlled speed of travel of the hardening tip over the object surface, the hardening torch can be mounted on a standard straight-line oxyacetylene cutting machine.

The tool post of a lathe with variable feed can also be used as a torch holder.

Flame Hardening Cylindrical Surfaces

Cylindrical surfaces, both external and internal, can be successfully flame hardened. Three different methods are in common use, the choice of each depending on the length and diameter of the cylindrical object.

(*a*) *Spinning Method.*—Narrow bands of flame-hardened surface can be produced on cylindrical surfaces of small diameter, such as crankshaft journals, by spinning the surface at a speed of about 100 rpm. under a heating tip. The heating tip should be of sufficient size to cover the width

of surface to be hardened. When the entire surface to be hardened has been raised to the hardening temperature, the heating flames are extinguished and a quenching stream applied to the spinning surface. Larger diameter surfaces may require two or more such heating tips equally spaced around the cylinder circumference to increase the speed of heating or to reduce the depth of hardness penetration. The spinning method is the simplest for hardening cylindrical surfaces and should always be considered where the size and shape of the object to be hardened permit. Since the entire surface to be hardened is simultaneously raised to the hardening temperature, the flame adjustment, torch positioning and the nature and degree of quenching are not critical. In addition, the temperature of the heated surface can be accurately observed before applying the quench.

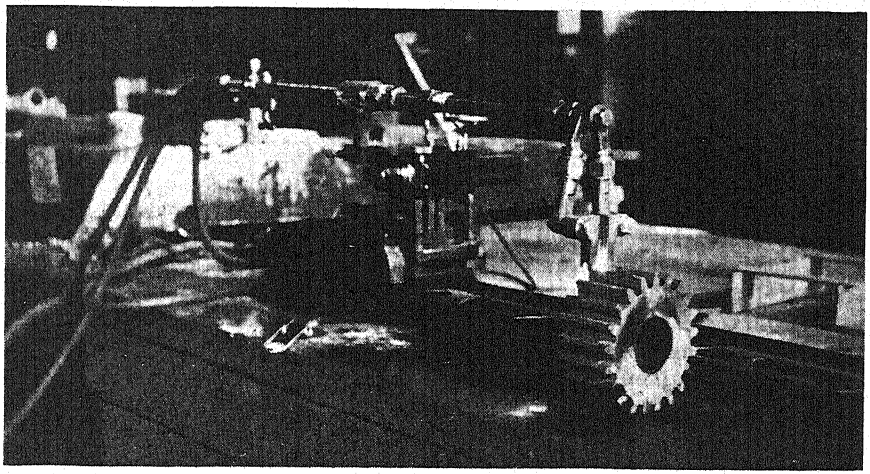


Fig. 4—Progressive Hardening of Spur Gear Tooth

(*b*) *Progressive Spinning Method.*—Cylindrical surfaces of extended length can be hardened by progressing a heated band $^1/_2$ to 1 in. in width, followed at a distance of $^1/_4$ to $^1/_2$ in. by a quenching stream, along the axis of the cylinder at the usual progressive hardening speed of 3 to 12 in. per minute. This is generally accomplished by placing the object to be hardened between centers and spinning at about 100 rpm. Heating torch and quenching line are mounted on the lathe tool post carriage. One or more heating tips, depending on the diameter of the object, are spaced at equal intervals on the object perimeter, so as to heat a narrow band to the hardening temperature. By moving the lathe carriage slowly, the heated band is progressed along the cylinder axis, followed by the quenching stream. An advantage of the progressive spinning method, aside from making possible the hardening of cylinders of extended length, is that much of this type of hardening can be done with standard oxyacetylene welding equipment which is generally available.

(*c*) *Progressive Method.*—Cylindrical objects of large diameter and extended length can be hardened by mounting in a lathe and turning at a

peripheral speed at the surface to be hardened of from 3 to 12 in. (most commonly 6 in.) per minute. The flame-hardening torch is mounted so that the multi-flame hardening tip progressively heats and quenches the desired width of band to be hardened. To prevent drawing the hardness at the overlap, an auxiliary cooling stream is sometimes used ahead of the hardening tip. By mounting the flame-hardening torch in the lathe tool post and moving the tool post carriage slowly along the cylinder axis, a spiral shaped strip 2 to 3 in. in width, depending on the width of the flame-hardening tip, can be hardened on the cylinder surface. Because of the possibility of developing surface checking by passing the flame over an already hardened area, it is common practice to avoid overlapping the heating passes. The narrow band of lower hardness, between the passes, is generally not objectionable on broad bearing surfaces.

Flame Hardening Irregular Surfaces

Flame-hardening tips can be designed to fit irregular contours such as cam surfaces or lathe spindle noses. In many cases, however, it is preferable to split up such a contour into several parts and harden each part of the contour as a separate operation. The resulting simplifications in tip design considerably reduce their cost and promote easy operation. In hardening gear teeth, the tooth profile is divided into two parts and heating tips are designed to fit each half of the tooth contour. Spur, sprocket, worm and herringbone gears are hardened by mounting the tips in a yoke at a fixed distance apart and providing for uniform motion of the tips along the tooth.

Special equipment is required in the case of worm and herringbone gears to rotate the gears as the tips move in a straight line along the gear axis, and with bevel gears for varying the spacing of the hardening tips and the speed of torch travel to accommodate the varying cross-section of the tooth. Gear-hardening machines, incorporating these features, are made by several companies manufacturing gear-cutting equipment.

Heat Treatment of Flame-Hardened Parts

Parts not subjected to high impact stresses in service are flame hardened without further heat treatment. Parts which are subjected to high impact stresses in service are frequently given both pre- and post-flame hardening heat treatments.

Large forgings and castings are normalized, annealed and stress relieved to improve the grain structure and to reduce strains which might cause distortion during flame hardening. Gears are commonly furnace hardened to 250–300 Brinell to secure the necessary strength in the core. Flame hardening the contact surfaces of the gear teeth to 400 or more Brinell does not affect the tensile strength of the core except in a very shallow tempered zone under the flame-hardened area.

Post-heat treatment should be applied to parts which are subjected to high impact stresses in service to reduce strains produced by flame hardening. Such heat treatment generally consists of a stress relief at 350–500°F. It has been found that in this temperature range, a considerable improvement in fatigue and shock resistance is obtained with very slight reduction in indicated hardness.

Economics of Flame Hardening

The cost of flame hardening per unit of surface treated will depend on a number of factors including set-up time, rate of torch travel, size of hardening tip, depth of hardness penetration required and the relation of the surface to mass of the object treated. The values of gas volume per unit of surface hardened and tip speed given below should be regarded as a very rough approximation to indicate the order of magnitude of these items.

The gas consumption required per square inch of surface treated will vary from 0.25 cu. ft. of oxygen and 0.25 cu. ft. of acetylene for a depth of hardness under $^1/_8$ in. to 0.5 cu. ft. of each gas for a depth of $^1/_4$ in. Greater depths of hardness require corresponding increases in gas consumption. The time required for flame hardening can be similarly approximated, by allowing for a tip speed of 4 in. per minute for $^1/_4$-in. penetration and 8 in. per minute for $^1/_8$-in. penetration. This factor is particularly affected by the form of the object hardened and by the volume of flame supplied by the hardening tip used. A 3-in.-wide flat tip, progressively hardening a section to a depth of $^1/_4$ in. will harden 12 sq. in. per minute and will consume approximately 0.5 cu. ft. of each gas per square inch of surface hardened.

FLAME SOFTENING*

Ferrous metals which have been hardened by heating above their A_3 critical temperatures and subsequently rapidly cooled can be softened with the oxyacetylene flame. This softening effect can be produced either by heating the metal above the A_1 point, followed by slow cooling (annealing), or by holding the metal for a longer period at a temperature below the A_1 point (tempering). The action of the oxyacetylene flame in full annealing is identical with that in flame hardening and consists in rapidly heating the metal above the A_3 temperature. Because of the rapid heating effect of the flame, differential softening can be obtained as well as differential hardness.

General Requirement for Flame Softening

The flame-softening process has been used for many years to restore ductility to auto body sheet which has been work hardened in deep drawing operations, heat from an oxyacetylene hand torch being applied to deeply drawn areas. Some use of flame softening has been made in reducing hard spots on steel and cast-iron castings before machining as well as to produce softened areas that can be machined on objects which have been heat treated to high hardness.

The major requirement for flame softening is in connection with machine cutting of higher tensile strength steels, which are coming into increasing use. In the cutting operation, the metal adjacent to the kerf is heated above its A_3 point and is rapidly quenched by conduction of heat into the cold body of the object cut, producing, in higher carbon and alloy steels, a shallow zone of increased hardness at the cut surface. A similar hardening

* For detailed discussion of this subject, see "Cutting and Tempering of Structural Steels," by H. H Moss in THE WELDING JOURNAL, January 1938, pp. 7–20.

effect is also produced by shearing, friction sawing and other methods of mechanical severing.

Plain carbon steel under 0.35% carbon may be flame cut without raising the hardness of the cut surface to undesirable limits. Higher carbon and high-strength low alloy steels are hardened by the cutting flame. Where such cut edges must be cold formed or machined, or where they must pass standard bend tests, it is necessary to reduce or remove the hardened effect in the edges. Certain specifications require the removal of from $1/8$ to $1/2$ in. of material from flame-cut surfaces of high-tensile structural steel. The flame-softening process provides a simple means of reducing the hardening effect of flame cutting on such steels.

Flame-Softening Procedures

Flame-softening procedures fall into two general classes: Preheating and Postheating. In preheating, the temperature of the metal along the cut line ahead of the cutting jet is raised to about the A_1 point in order to reduce the quenching action of the cold base metal. Objects which can be conveniently furnace heated to temperatures of 800–1200°F., such as locomotive valve gear, show no hardening of the cut surface. Such furnace heating is more economical than flame softening, particularly on thick sections. Preheating with the oxyacetylene flame is limited to thicknesses of $1^1/_2$ in., heating from one side only, and to 3 in., heating from both sides.

Figure 5(a) illustrates, schematically, the set-up for preheating or postheating with the oxyacetylene flame, heating from one side of the steel plate.

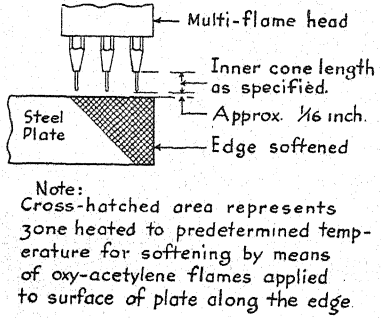


Fig. 5 (a)

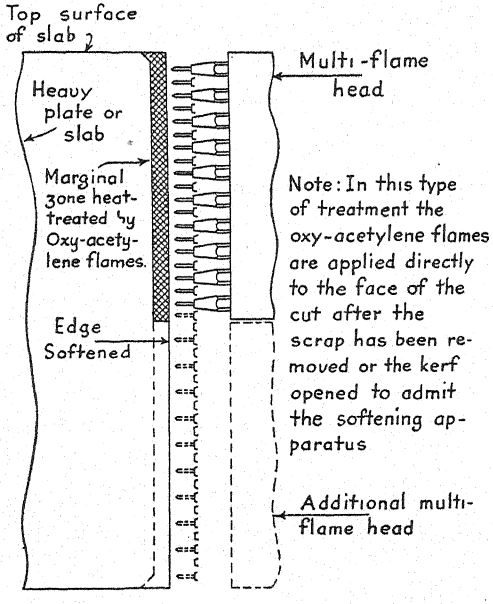


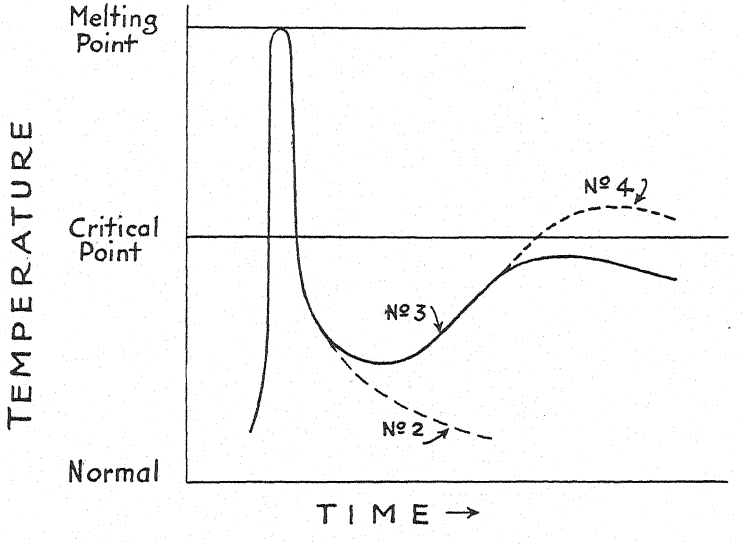
Fig. 5 (b)

Heating tips similar to those used in flame hardening are used in flame softening by preheating. Sufficient of these tips are mounted ahead of the cutting tip to preheat the plate at a speed of continuous forward motion equal to the cutting speed. Care must be used in adjusting the preheating flames of the cutting tip to avoid burning the top edge of the preheated plate.

In postheating, the heating tips are mounted immediately following the cutting tip. Sufficient heating tips are used so that the speed of softening is equal to the cutting speed, and both operations proceed simultaneously. The flame-softening effect in postheating is more complex than in preheating, and combines a retarding action on the cooling rate, with an actual softening effect on the already hardened surface. Depending on the nature of the steel, the postheating treatment combines more or less of each of these actions.

The temperature imparted to the plate in postheating can be either above the A_1 point (super-critical anneal) or below this point (sub-critical temper). Figure 6 shows diagrammatically the relation of temperature and time in flame cutting (curve No. 2), in sub-critical tempering, heating from one side of the plate (curve No. 3), and in super-critical annealing, heating from one side of the plate (curve No. 4).

The thickness of plate which can be softened by simultaneously postheating after flame cutting is limited to approximately $1^1/_2$ in., heating



Curve Nº 2 - Plain Flame Cutting.
Curve Nº 3 - Type Nº1 Treatment, Postheat below Critical.
Curve Nº 4 - Type Nº1 Treatment, Postheating above Critical.

Fig. 6

from one side only, and to 3 in., heating from both sides of the plate. The nature of the steel and the severity of the tests to be met affect the maximum thickness of plate that can be simultaneously cut and softened by postheating. In general, the cut edges of plates thicker than 3 in. are more economically softened by removing the scrap and applying the heating tips directly to the surface of the cut face. This type of treatment is not limited by thickness and has been used on plate up to 12 in.

In flame softening a hardened cut face, the type of treatment used, whether a super-critical anneal or a sub-critical temper, will depend on the nature and hardening properties of the steel. The disposition of the heating flames and the rate of progression along the cut surface will vary with the sluggishness of the steel to the tempering action. This treatment is shown schematically in Fig. 5(b).

Typical Results

Figure 7 indicates typical flame-softening effects, on steels of commercial interest, as determined by H. H. Moss.* Tests were made on steel between $1/4$ and $1\,1/2$ in. in thickness and with initial hardness varying from 150 to 250 Brinell. The hardness of the flame cut face varied from 200 to 550 Brinell depending on the type of steel used. Flame softening during cutting, both by the preheating and postheating method simultaneously, indicated that the softness of the parent metal could be largely retained

* *Loc. cit.*

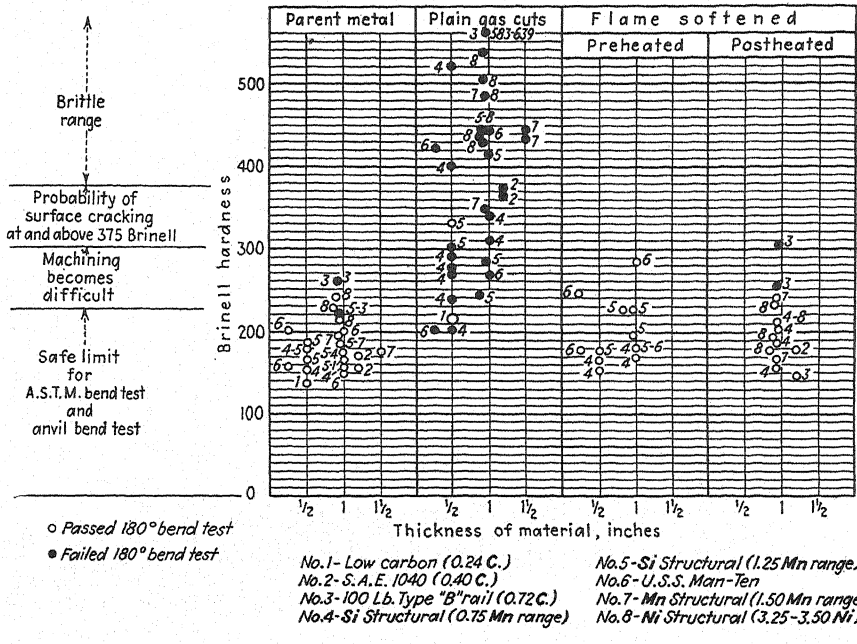


Fig. 7—Typical Flame Softening Effects

after flame cutting. Of particular interest was the fact that the majority of the steels so treated satisfactorily passed the 180° Anvil Bend Test.

The actual gas cost involved in flame softening will vary somewhat with the type of treatment required. In general, the gas consumptions are roughly similar to those common to flame hardening. For rough estimating purposes, approximately two cubic feet of oxygen and two cubic feet of acetylene will be used to soften one linear foot of one-inch-thick steel, on one side of the kerf, when cutting and simultaneously heating from one side of the plate. The consumptions will be slightly lower per unit area when simultaneously heating from both sides of the plate. When softening the cut face, after removal of scrap, the gas consumptions will be reduced to approximately 0.06 cu. ft. of each gas per sq. in. of surface softened. Since this operation is performed independently of cutting, there will be additional labor costs involved which are not present in the simultaneous cutting and softening procedures.

FLAME STRENGTHENING

Flame strengthening is the use of the oxyacetylene flame in a heat-treating operation to increase the tensile strength of local areas which will be highly stressed in service. In application, it is practically identical with the flame-hardening treatment since hardness and tensile strength are paral-

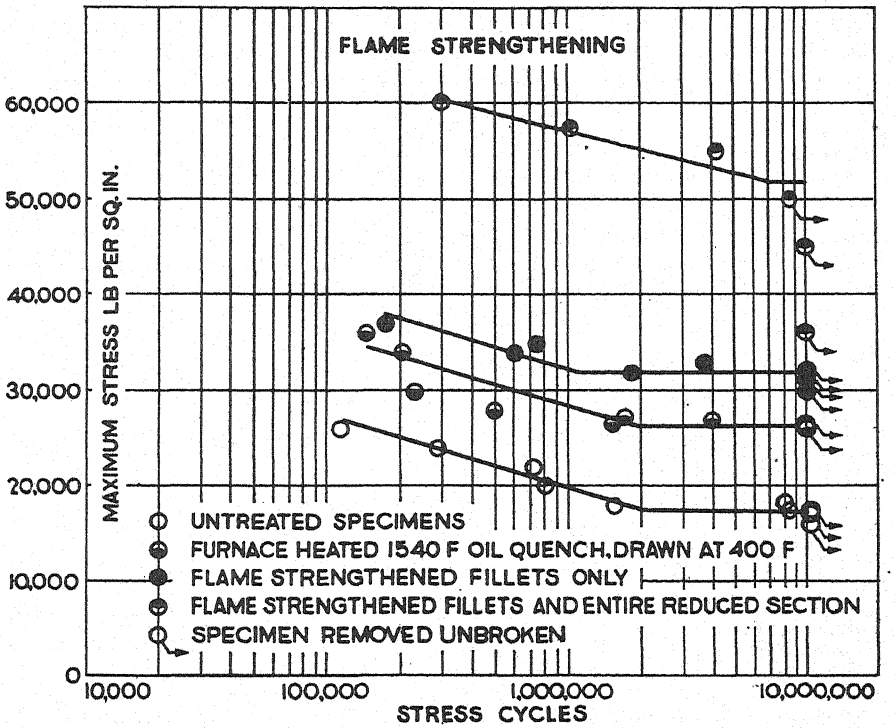


Fig. 8

lel characteristics in steel. The purpose of flame strengthening differs from flame hardening in that the intent is to strengthen parts locally in the regions which will have to withstand the most severe service conditions. The process is directed particularly at parts which are to be subjected to widely and frequently varying stresses conducive to failure by fatigue.

In flame strengthening, less drastic quenches are used than in flame hardening, and a somewhat lower hardness value obtained, in order to combine a certain measure of ductility with increased tensile strength. Tempering of flame-strengthened parts is also recommended to reduce stresses set up in the strengthening treatment. The process has not been completely investigated to the point where general recommendations of strengthening procedure can be made, but preliminary evidence indicates that it will take its place with Flame Hardening and Flame Softening as a standard flame-treating process.

Figure 8 illustrates the results of a series of tests of the fatigue resistance of S.A.E. 1045 steel after various heat treatments. The test specimens consisted of rounds of $^1/_2$-in. diam., reduced sharply to $^7/_{16}$-in. diam., causing a stress variation of 1.5 to 1 at the point of reduction in diameter. As seen in Fig. 8, the endurance limit of the untreated test specimen was 18,000 psi. Specimens oil quenched from 1540°F., and drawn at 400°F., showed fatigue limit of 26,000 psi. Specimens heat treated at the fillet produced by the change of section gave 32,000 psi. Specimens flame strengthened in the fillet and on both sides of the change in section gave 52,000 psi. These results are sufficiently promising to indicate that a further development of the flame-strengthening process will provide an answer to many problems of local stress concentration.

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CHAPTER 16A

OXYGEN CUTTING*

History, Chemistry of Oxygen Cutting, Torch and Tip, Hand Cutting, Machine Cutting, Fundamental Requirements, Basic Cutting Procedure, Drag, Maximum Tip Efficiency, Tip Size, Cut Quality, Precision, Oxygen Purity, Fuel-Gases for Oxygen Cutting, Heavy Cutting, Metallurgical Effects of Oxygen Cutting, Chemical Changes, Effects of Alloying Elements, Heat Treatment, Multiple and Stack Cutting, Lance Cutting, Cast Iron Cutting, Flame Machining.

THE importation of the first cutting torch into this country about 1907 made a profound change in industrial practice having to do with the shaping of steel. The limit of shears is on the order of $1^1/_2$ in.-thickness for the low carbon steels cut cold and less for the higher carbon and alloy steels. Other methods of shaping the heavier sections are expensive and generally require that the work be transported to the machine. The adoption of the oxyacetylene cutting torch, which is capable of cutting metal 40 in. or more in thickness, provided a tool that could be taken to the job with very little effort and could be used for cutting not only in straight lines but could, by means of mechanical guiding, be used for cutting all manner of shapes to fairly accurate dimensions.

For a long time the torch has been used to advantage by the foundry for removing risers and sprues from castings and recently extensive use has been made of the torch for shape cutting from rolled steel of parts to be used for fabrication by fusion welding. The combination of the oxygen-cutting† process with fusion welding has done much toward providing an economical means for fabricating machine tools, pressure vessels and building structures.

Extensive use has also been made of the process in the production of jigs, fixtures and parts, the limited number of which does not justify the expense of dies or patterns. In addition, it is possible by means of oxygen

* Prepared by a committee consisting of J. J. Crowe, Air Reduction Sales Co., *Chairman;* G. M. Deming, Air Reduction Sales Co., and J. H. Zimmerman, The Linde Air Products Co.

† The term "oxygen-cutting" is used in this presentation as a more significant term than "flame-cutting."

shape-cutting machines and simple templates or drawings to undertake quantity production of parts, even though such parts may necessitate a considerable degree of precision.

Probably because oxygen cutting has provided a convenient and readily portable means for the cutting and shaping of steel at a low cost, little attention has been given to the possible economies involved in the application of the process. The result of this lack of attention and failure to properly control the many variables involved in the simple process of oxygen cutting has frequently resulted in excessive costs and in some cases unjust rejection of the process. The present tendency to more critically examine the fundamental principles and practical details of the oxygen flame-cutting process is therefore most opportune.

History

Cutting steel by means of a jet of oxygen directed on to a portion of the steel, previously heated to red heat, was apparently first discovered about 1887 by Thomas Fletcher. However, the first practical torch for combining the heating operation with the oxygen cutting operation was not introduced until 1901. Within a few years afterward mechanically guided oxygen cutting torches were developed to a practical stage.

The first applications of oxygen cutting were not very indicative of the prestige which the process subsequently attained because these early applications were solely for safe-cracking. In fact, public resentment over the process was so great that it was seriously proposed that it should be prohibited by law. Aside from these earlier unfortunate applications the process has been increasingly used for a great variety of tasks of great worth to society. Today it constitutes one of the major tools of industry.

Chemistry of Oxygen Cutting

If iron or steel is heated to a temperature of approximately 1600°F. and comes in contact with oxygen, the iron is immediately oxidized. The phenomenon of combustion of iron by oxygen is similar to the combustion of coal in a furnace. If the coal is heated to the kindling temperature in an atmosphere of air (air contains 20% oxygen) the coal burns or oxidizes. Likewise if iron is heated to the ignition or kindling temperature in contact with oxygen it burns or oxidizes very rapidly.

The chemical equation for this reaction is as follows:

$$3Fe + 2O_2 = Fe_3O_4$$

In the process of oxygen cutting, advantage is taken of the capacity of pure oxygen to combine rapidly with iron that has been heated to the kindling temperature. Theoretically, 4.6 cu. ft. of oxygen will oxidize 1 lb. of iron to Fe_3O_4, but in practical cutting operations where proper attention is given to the variables involved, the amount of oxygen used is appreciably less than theoretical consideration would indicate. This is because all of the iron is not oxidized to Fe_3O_4. Some unoxidized, or only partly oxidized, metal is removed by the force of the rapidly moving oxygen stream. Moreover, some of the oxygen necessary for the combustion of the iron is supplied by the surrounding atmosphere, so that under favorable conditions the actual oxygen supplied through the cutting torch is

appreciably less than the "theoretical" requirement. Analysis of the slag in some instances has shown over 30% to be iron which has not been oxidized.

The heat generated by the combustion of one pound of iron is 2900 Btu's and the high temperature resulting from the liberation of this heat melts some of the iron. This molten iron is swept out by the rapidly moving stream of oxygen and iron oxide. Most of it is oxizided before it is blown clear of the cut and thus furnishes heat for melting another layer of iron at the active cutting front. Because the oxidation is not an instantaneous process, the heat developed by the oxidation of the iron removed from the uppermost level of the cut is liberated for the most part at a somewhat lower level. For this reason it is necessary to supply the thermal deficiency at the uppermost level by means of preheating flames at the torch tip which burn continuously while the torch is in motion.

Many of the impurities and alloys present in steel when the amounts are not large are oxidized or dissolved in the slag without interfering with the progress of the cut, but this is not true of some of the alloying elements when present in appreciable amounts. While steels containing these refractory alloys can be cut, the technique required may be quite different from that used with the straight carbon or low alloy steels.

Torch and Tip

Essentially, the cutting of iron or steel by the oxygen-cutting process merely involves the direction of a jet of pure oxygen into an area that has been previously heated to the ignition or kindling temperature, about 1600°F., and as the iron is oxidized, slowly and uniformly moving the jet along the line to be cut. If the cutting is to be continuous, however, it is necessary to supply heat to the steel just ahead of the oxygen stream. In the early applications of the process, the required heat, called "preheat," was supplied by the flame of an oxyacetylene welding torch. In fact, the cutting operation was carried out with an oxygen nozzle attached to a welding torch, the heating flame of the welding torch being positioned in advance of the oxygen jet. Such an arrangement had the disadvantage that it required careful manipulation to insure that the preheating flame always preceded the cutting jet, and this was particularly difficult when the contour of the desired cut was other than a straight line.

Modern torches are equipped with separable "tips" in which the oxygen-cutting jet is surrounded at a proper distance by several preheating flames (see Fig. 1). With this arrangement the torch may be moved in any direction without losing the effect of the preheating flames. Individual valves are provided for controlling the gas flow and so arranged that there is independent control of the fuel gas used for preheating, the oxygen for preheating and the oxygen used for cutting.

Torches, or blowpipes, are of two types: first, those in which the fuel gas and oxygen for the preheating flames are mixed in the tip; and second, those in which the mixing takes place in the head or some location back of the head, as, for example, in the body of the torch. This latter type is designated as a torch of the "premixed" type. If both the oxygen and fuel gas are under appreciable pressure the torch or blowpipe is designated

as a "pressure" torch (or blowpipe) and when the fuel gas is at a lower pressure, generally a fraction of a pound per square inch, and supplied to the flames through the aid of an injector operated by the preheating oxygen, the torch or blowpipe is designated as a "low pressure" or "injector" torch.

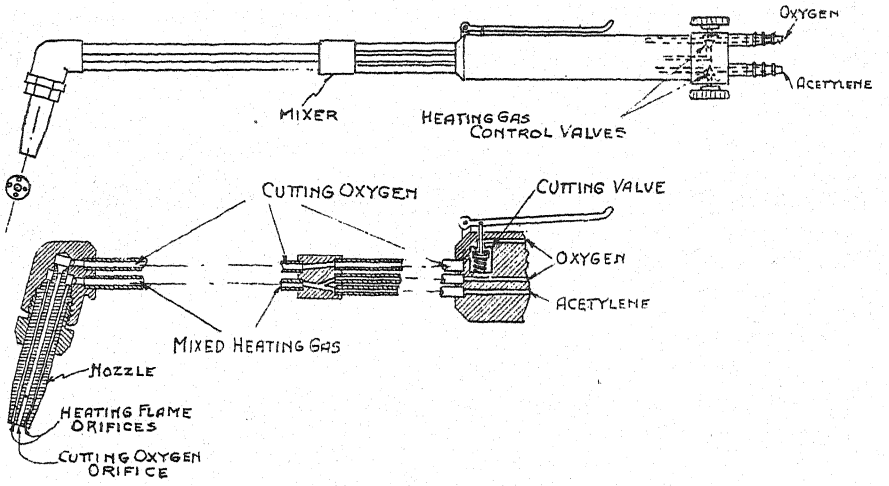


Fig. 1—Typical Cutting Torch and Schematic Cross Section (Premixed Type)

Hand Cutting

Before beginning a cut, a proper "size" of tip must be selected which is appropriate for the particular thickness and quality of the steel to be cut. Cutting tables or cutting data supplied by the manufacturer of the torch afford a rough guide in the selection of the proper tip. Besides the selection of the tip and its insertion into the torch head, where it is firmly secured in place by appropriate means, the torch must be connected by hose lines to suitable oxygen and fuel gas pressure regulators. The gases are then supplied to the torch at appropriate pressures, which are also roughly specified by the manufacturer's table of cutting data. The torch is then lighted and held in readiness for starting the cut.

In most cases, oxygen cuts are started at the edge of the work piece. The cutting torch is held so that the ends of the inner cones of the preheating flame just clear the surface of the material. When a spot of metal at the top of the edge has been heated to a bright red (the kindling temperature), the cutting oxygen jet is turned on. The metal in the immediate path of the cutting jet oxidizes and, as the torch is moved slowly and steadily along the line to be cut, separation of the metal is effected. In oxygen cutting ordinary steel, the tip should be held vertically at a uniform distance above the surface and advanced steadily at the proper speed, with as little wavering as possible. If the speed of traverse is too great the sparks and slag emerging from the bottom of the cut will trail back prominently and when this is the case there is imminent danger of

the stream suddenly failing to completely penetrate the steel. Accordingly, the operator who is guiding the torch by hand must closely observe the slag emerging from the bottom of the cut or the general nature of the course pursued by the oxygen and slag stream as it traverses downward through the steel, and he must readjust the speed of traverse accordingly. If the movement is too fast, the cut may be lost, that is, the oxidation reaction ceases and it becomes necessary to shut off the cutting oxygen stream and again preheat the metal at the forward edge of the cut before reopening the cutting oxygen valve. Operators become very proficient in guiding the torch by hand, and the resultant cuts may be fairly smooth and true as to required contour.

To assist in following the line of cut without wavering, use is often made of straight edges, or formed templates against which the torch tip is steadied. Another aid often used is small wheels fitted to the torch head and arranged to roll along the work and so adjusted as to keep the end of the tip at a proper distance from the work. For cutting circles, a trammel bar may be attached to the torch head and to a fixed center.

Machine Cutting

For many operations, the advantage of mechanically holding, guiding and advancing the torch or blowpipe over the work was recognized early in the history of oxygen cutting. It was evident that, when practicable, this would result in better workmanship, accuracy and economy. Oxygen cutting machines have been developed to fill this demand.

Present-day oxygen cutting machines are comparable with machine tools. They are capable of making oxygen cuts with jig-saw flexibility and of such high quality and accuracy as to frequently require no further finishing. Machines are available, either manual or motor driven, either semi or nearly fully automatic, portable or stationary, and of capacities suitable for practically all classes of work of almost any size or thickness. Cutting machines are frequently equipped with more than one cutting torch, centrally controlled and guided, and will oxygen-cut a number of identical shapes simultaneously, thereby effecting marked economies where a high production rate prevails. Still other types of machines will crawl around pipes, making one or two square or beveled cuts as desired. Nearly every conceivable requirement is covered by the wide assortment of machines now available.

Straight line machine oxygen cutting is even simpler than free hand flame cutting. Once the machine and gas pressures have been adjusted the torch follows the line of cut automatically. It need only be advanced uniformly at proper speed, by turning a crank or handwheel or by means of mechanical power. Some portable motor-driven machines run on sections of straight track, which guide the machine and the torch mounted upon it.

As the cut progresses, the operator watches the flow of slag or oxide. Any tendency toward pocketing and other defects may be instantly recognized by abnormalities in the movement of the slag and may be corrected by appropriately varying the speed or the oxygen pressure.

Machines should be located and set up in such a manner as to eliminate shocks and vibrations while cutting. The work should be supported

so that continuity of cut without interference is assured and parts or scrap pieces cannot fall when cut, in a way that might endanger the operator or machine. In flame-cutting thick sections, particular attention should be given to proper apparatus set-up, including manifolds, regulators and hose of suitable type and to provision for an ample gas supply for the job in hand.

Shape cutting machines are mostly motor driven. Some have tracing devices which are manually guided around the outline of a drawing or a templet of the required shape. One or more torches mounted on the machine duplicate the motion of the tracing device over the work, thereby cutting the shape, or shapes, traced. Some machines are fitted with motor-driven guide rollers, which automatically follow a templet of the required shape, simultaneously controlling the movement of the torch so as to cut the same shape. Motor-driven magnetized rollers, which adhere to steel templets as they advance automatically around the contour, are a feature of certain machines. Some typical shapes, for which machine oxygen cutting is adapted, are illustrated in Fig. 2.

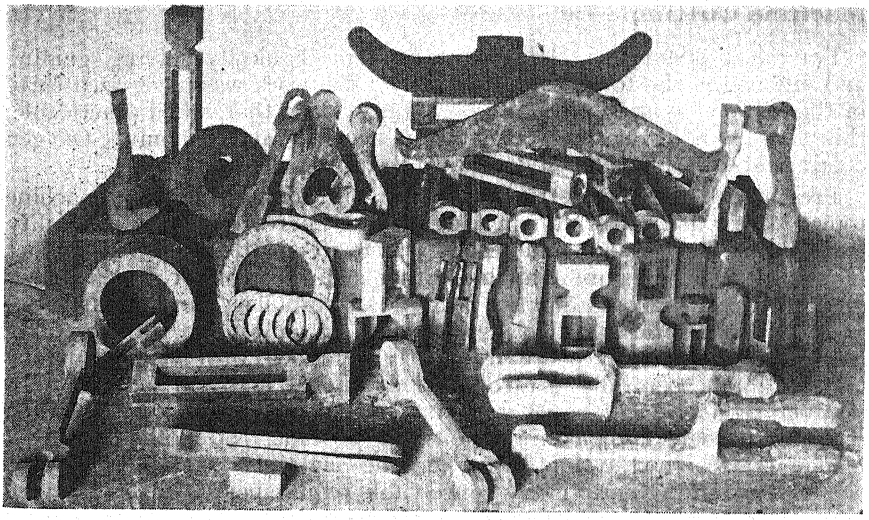


Fig. 2—Typical Shapes Made with Machine Oxygen Cutting

Most oxygen cutting machines may be adapted to circular cutting. With some, a radius rod with an adjustable center point is furnished. The point is placed in a center punch mark at the center of the circle and the machine and cutting torch travel around the circumference at the radius set. Machine oxygen cutting of discs, flanges, heads and similar circular parts has wide industrial application.

Fundamental Requirements

It is necessary to be definite when referring to the "quality of the cut." A satisfactory commercial cut may be defined as one fulfilling the following requirements:

1. A sufficiently short drag; that is, the line markings on the face of the cut (Fig. 3) should approach the condition of being straight up-and-down rather than dragging back so far that a large (lower) corner is not cut and must be broken off.
2. Sufficiently smooth sides of cut, i.e., not grooved, fluted or ragged.
3. Satisfactory slag condition. For most production work there should be no firmly adhering slag that involves an appreciable expenditure of labor for its removal.
4. The upper edges of the cut should be sufficiently sharp for the requirements of the particular job.

The first two features just mentioned, viz., length of drag and smoothness of cut, are generally of greater practical importance than the other two, and of these two the length of drag is of greater fundamental importance. In fact, if one merely considers the length of drag in deriving the most economical cutting conditions it will be found that, in general

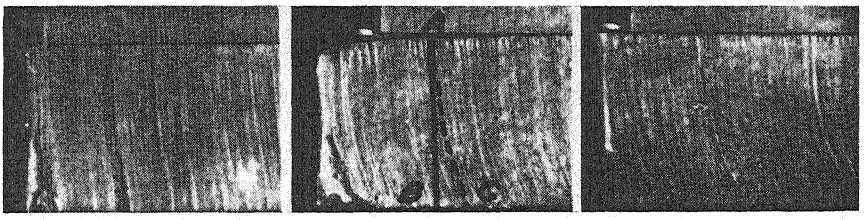


Fig. 3—Specimens of One-Inch Cuts. Left: Drag 0.11 In. Lower Corner Completely Severed. Center: Drag 0.20 In. Corner Completely Severed. Right: Drag 0.22 In. Lower Corner Not Completely Severed. (Fracture in Lower Left-Hand Corner Not Clearly Revealed by Photograph)

these conditions are not inconsistent with the requirements for a sufficiently smooth cut, satisfactory slag condition and sharp edges.

The most important independent variables are as follows:

1. Size of the cutting orifice.
2. Oxygen operating pressure.
3. Speed of cutting.
4. Thickness of the material being cut.
5. Quality of the material.
6. Purity of the oxygen.
7. Intensity of the preheat.
8. Angle of incidence of the cutting stream to the upper edge.
9. Smoothness of cutting orifice.
10. Cleanliness of the end of the tip.

The rate of oxygen consumption must be thought of as dependent upon the first two of these variables and not as a separate independent variable.

For any given cut each of the variables listed should be so evaluated that the precise quality of cut desired may be realized with the minimum aggregate cost in oxygen, fuel gas, labor and overhead.

Basic Cutting Procedure

Because of extreme variation in such things as the quality of the steel

the cleanliness of the tip and the skill of the operator, as well as in the acceptable standards of performance, it is not possible to establish a universally dependable table of cutting pressures, tip sizes and speeds. Cutting tables must not be looked upon as cutting "specifications" but rather as approximate cutting "guides" which fit certain average conditions sufficiently close so that trial cuts may be made with a fair presumption of success. Following the inspection of the trial cut, more practical working conditions for the particular job may be evolved by carefully and appropriately varying the speed of cutting, the tip size and the operating pressure.

Because cutting tables are but preliminary and approximate guides it is but natural that different manufacturers of cutting equipment supply somewhat different tables of cutting data. Figure 4 is a plot of cutting

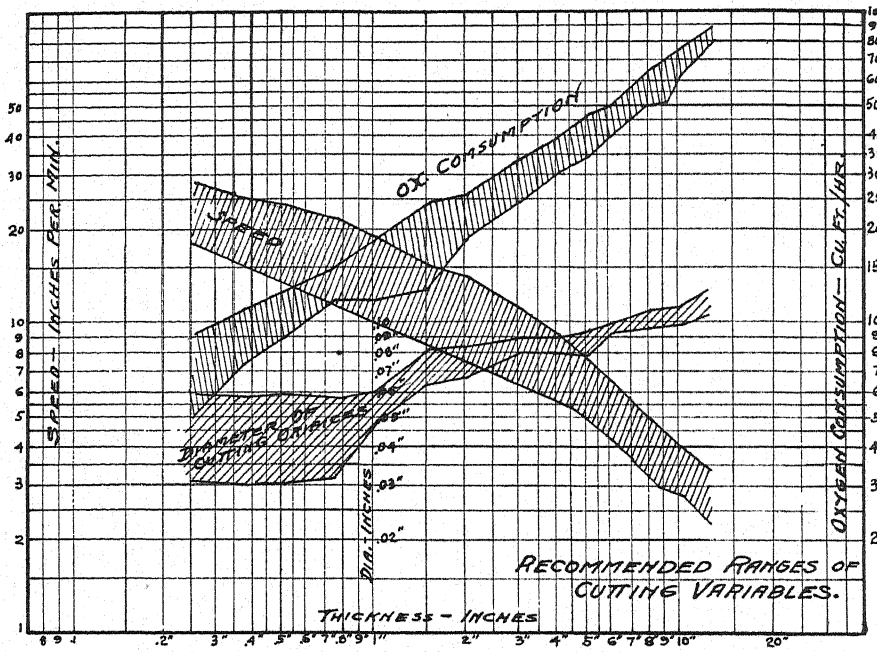


Fig. 4

data from a great variety of cutting tables, both of American and of foreign origin. For each of the cutting variables involved a zone is shown which expresses the range of values specified by different authorities for cutting the given thickness of steel. Where a cutting table is not available for a given series of cutting tips the values suggested in Table 1 may be employed which has been compiled from averages of many of the latest and most authoritative cutting data. It is assumed that:

1. The plate being cut is clean and free from rust or paint.
2. Square edged (90°) cuts are being made.
3. The cut is to be straight (no curved contours).
4. The plate is of low carbon steel of good quality.
5. The fuel gas is acetylene.

6. The oxygen is of 99.50% plus or minus 0.10% purity.
7. The angle of incidence of the cutting stream with respect to the surface of the plate is 90°.
8. The steel is at room temperature.
9. All other conditions are substantially "normal."

Table 1—Approximate Guide for Machine* Cutting Steel Plate

Plate Thickness, In.	Speed In./Min.	Drill Size of Cutting Orifice	Oxygen Pressure Lb./Sq. In.
1/4	20	62	30
		60	25
		58	20
3/8	19	57	35
		56	30
		55	25
1/2	17	56	40
		55	35
		54	30
3/4	15	55	45
		54	40
		53	30
1	14	55	55
		54	50
		53	45
1 1/2	12	54	55
		53	50
		52	45
2	10	53	55
		52	50
		51	50
3	8	47	55
		46	50
		45	45
4	7	45	60
		44	55
		42	50
6	5	42	60
		41	55
		40	50
10	3 1/2	36	75
		34	70
		30	65

* The tip sizes and operating pressures specified in this table are also approximately correct for hand cutting.

For each specified thickness of material, three different sizes of cutting orifices are indicated in Table 1. This has been necessary because there is no common standard of cutting orifice sizes employed by tip manufacturers. From each group of three orifices the orifice should be selected which is found in the particular series of tips being used.

After an operator has acquired sufficient experience with the particular thickness and quality of the steel involved, he may depart rather widely from the conditions specified, particularly in the direction of lower operating pressures and higher speeds, provided he does so cautiously and with due recognition that one or two successful cuts at greatly reduced pressure or increased speed do not justify standardizing upon the revised practice. At any rate, haphazard cut-and-try methods are to be condemned. It is particularly important to observe that frequently there is a pressure which is just right, and that an increase or a decrease of more than one or two pounds will lead to definitely inferior cutting conditions.

In general, the cutting conditions listed in Table 1 are very conservative. As a rule, experience with the given steel and *methodical* evolution of more specifically applicable cutting conditions will result in greatly decreasing the cutting costs. There are times, however, when, particularly with certain alloy steels, the cutting conditions specified in the table will be inadequate. Nevertheless, whatever the cutting conditions employed for any given cut and whatever the nature of the steel which is being cut, the procedure which should be followed in improving the operation during subsequent cuts is much the same. It should be understood in this respect that the evolution of the most satisfactory cutting conditions for any

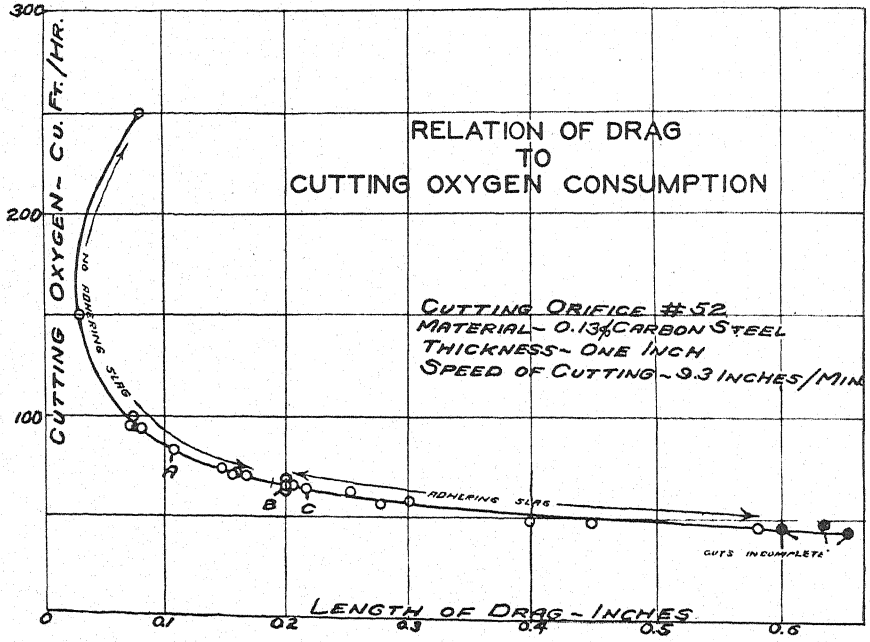


Fig. 5

given thickness and quality of steel, corresponding to specific standards for the appearance of the finished cut, is a process which calls for intelligence, experience and skill if the optimum performance is to be realized. The details of the process may be varied somewhat according to the

preference of the operator, but they should by all means be systematic and in accordance with the principles discussed in the following pages.

If a cut fails to propagate continuously, and if the failure is obviously a failure to propagate at the upper surface of the steel, the fault may be that the surface condition of the steel is not satisfactory for continuously propagating the cut with the given preheat intensity. If the steel is clean and free from rust, heavy scale or paint, exceedingly light preheat will ordinarily be adequate, but even with such steel it occasionally occurs that the cut will be interrupted as the result of some slight slag defect at the surface of the steel that is not obvious upon superficial examination.

Drag

Let a series of cuts be made with a given tip at a constant speed and with varying oxygen operating pressures. Next, let a line, such as AB, Fig. 3, be inscribed normal to the upper edge of each cut and one face of the cut. If the particular drag-line which originates at A be followed downward to its lower terminus, C, then the distance BC may be recorded as the length of drag involved for that particular cut. If for any given tip the oxygen operating pressure necessary to give rise to each particular length of drag (the speed being constant) is plotted against this drag, a curve somewhat similar to that of Fig. 5 is obtained. For the sake of simplifying the analysis, the oxygen consumptions of the cutting jet may be plotted against the drag, as in Fig. 5, instead of the corresponding operating pressures. (Note that the oxygen used by the preheating flames is not included.)

Figure 5 illustrates the following facts with regard to drag lines:

1. The increase of the oxygen consumption becomes greater (i.e., the pressure must be increasingly augmented) as the length of drag decreases, and for very short drags a slight decrease in the drag length can be procured only at the expense of a very greatly increased oxygen consumption. This fact is of fundamental importance when considering the question of cutting economy.

2. Except for very low cutting speeds, a certain minimum length of drag is characteristic of a given speed and tip regardless of the operating pressure (or the oxygen consumption). This "minimum drag" is about 0.03 in. at an oxygen consumption of approximately 170 cu. ft. per hour in the case of Fig. 5. The minimum is greater than that indicated by Fig. 5 when the speed of cutting is greater and less when the speed is less.

3. An increased drag may result if an attempt is made to obtain a drag shorter than the minimum by increasing the operating pressure beyond that at which the minimum drag is obtained. Hence, such an attempt will not only result in very costly operation, but may prove worse than useless.

The most searching question that can be asked when considering the economics of oxygen cutting is, "Just how short must the drag be to fulfill the requirements for a satisfactory cut?" If it is too short the cutting operation becomes expensive as a result of the greatly increased oxygen consumption. Figure 5 indicates that for 1-in. cutting at about 9 in. per min. with a No. 52 (drill size) cutting orifice the oxygen consumption for the minimum drag is over twice as great as for the drag of point A. If the drag is too long an uncut final corner may be the result. In the case of Fig. 5 uncut corners result from any drags longer than that of point B. Incidentally, the three cuts, A, B, and C of Fig. 5, are the identical cuts illustrated in Fig. 3.

In extreme cases considerable effort may have to be expended to break the uncut corner. At any rate, the appearance of a ragged final corner may often be a point of some importance. From another viewpoint an extreme length of drag is undesirable because of its detrimental effect upon the squareness and straightness of the edges of the cut in the case of circular or irregular cutting, although this effect is less than generally assumed. Again a very long drag may indicate that not much reserve oxygen is available above the minimum at which penetration of the plate is just barely possible, and as a result slag inclusions or other defects in the plate in the line of cutting may cause the loss of the cut.

In view of the above discussion, it is apparent that an effort should be made to select some definite length of drag as standard for any given operation. Merely to ignore the matter is to run the risk of wasting much oxygen as well as of obtaining poorer quality cuts. Some plants select the zero drag, or nearly zero drag, as standard. For shape cutting where sharp corners, or curves of short radii are involved, there is frequently justification for selecting so short a drag.

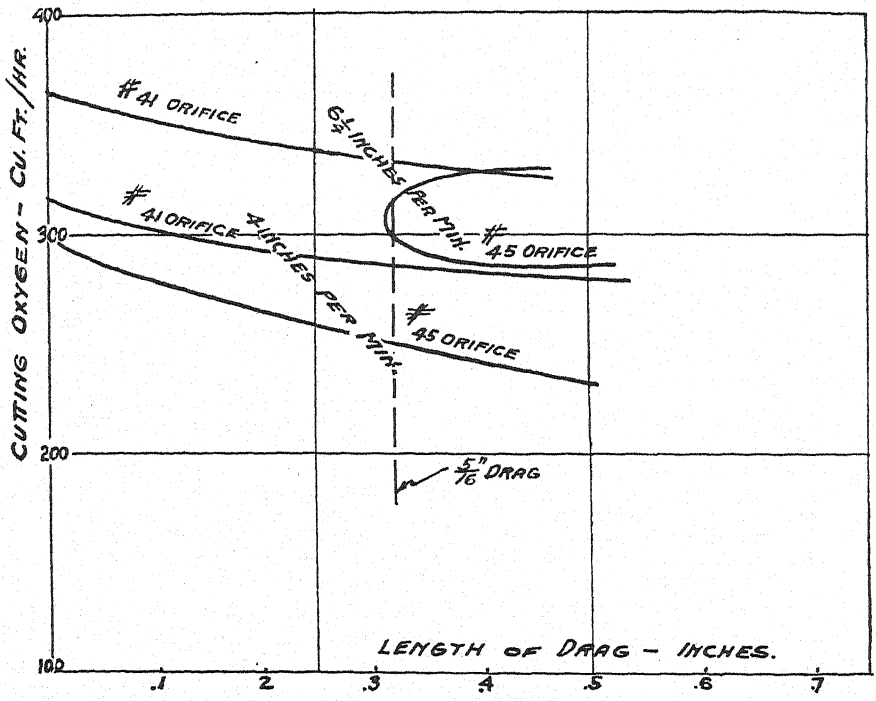


Fig. 6—Approximate Comparison of Cutting Orifices—6-Inch Cutting

Cutting studies such as those which form the basis of the data of Fig. 6 will enable the supervisor to determine whether zero drags are sufficiently desirable as to be economically justified. Referring to Fig. 6 it will be seen that if a No. 45 (drill size) orifice is employed a zero drag may be realized when cutting the particular steel if the cutting oxygen consumption

is about 300 cu. ft. per hour and the speed about 4 in. per minute. If, however, a drag of $^5/_{16}$ in. is tolerated, then with the same orifice and the same oxygen consumption a speed of $6^1/_4$ in. per minute instead of 4 in. per minute (a 56% increase in production rate) is possible. From another angle if it be assumed that for the zero drag cut a No. 41 orifice and a $6^1/_4$ in. per minute speed are employed then the oxygen requirement as indicated by Fig. 6 will be about 365 cu. ft. per hour. On the other hand, if a $^5/_{16}$-in. drag is selected, then at the same speed the cut may be made with the next smaller size of cutting tip (the No. 45 orifice) and the oxygen requirement will be reduced to 300 cu. ft. per hour.

It is thus obvious that in the interest of economy the drag should be as long as possible. If it is actually permissible, so far as the requirements for the finished cut are concerned, to employ much longer than zero drag it is quite likely that what hereafter will be referred to as a "standard" drag will be the limiting or maximum permissible drag, viz., a drag which is as long as possible without leaving an uncut final corner (see Fig. 3, the middle cut of which is a "standard" drag cut). For cuts whose drags are shorter than "standard" no uncut corner results because of the peculiar action of the oxygen stream at the completion of the cut. In some instances, particularly where the piece being severed is heavy enough to break the final corner by its own weight, and where there is no objection to the production of work which is characterized by large uncut corners, it may even be practicable to standardize on drags which are longer than "standard." In full recognition, however, of the possibility of both shorter and longer drags being more suitable in special instances, the term "standard" drag is nevertheless employed in the following pages both as a matter of convenience and because it is a standard which will be found to be quite generally satisfactory. It turns out that in the majority of cases the "standard" drag as above defined is also suitable for circular cutting and the cutting of irregular shapes. This "standard" drag may be expressed as follows:

Table 2

Thickness of Material in In.	Approx. Length of "Standard" Drag* in In.
$^1/_2$	$^3/_{32}$
1	$^{13}/_{64}$
2	$^7/_{32}$
2 to 6	$^1/_4$

* Based upon the assumption that the "final" edge of the work material is exactly perpendicular to the line of torch traverse.

Naturally, one may sometimes standardize upon the degree of off-square condition for a cut of known radius or upon the size of an uncut final corner, rather than upon the length of the drag. In some instances it may be easier to do this than to try to trace ill-defined drag lines in order that they may be measured, but even such methods indirectly make use of drag-lines as a basis of comparison because a given off-square condition or a definite size of uncut corner is the result of some particular length of drag. At any event, the shop which does not have some criterion of cut quality, either directly or indirectly related to length of drag, even if the standard is only an approximate one, will almost certainly experience excessive costs for its cutting operations.

Maximum Tip Efficiency

With the basic consideration clearly defined (viz., some definite standard of drag length), a certain tip size, operating pressure and speed of cutting should be selected to give rise to that length of drag. This should be done in such a manner as to involve the minimum cost. Cutting tables merely suggest trial conditions. The goal will be attained only by giving careful attention to such details as presented below.

To judge whether a given cutting operation is in line with the economy which may reasonably be expected of the particular cut some method of computing cutting efficiency is desirable. For this purpose there is sometimes used the ratio of the oxygen actually used to that which would have been required to oxidize the metal originally contained in the kerf to Fe_3O_4. This is not an ideal method, because, for one thing, such a figure of relative efficiency is unaffected by the width of kerf formed. Obviously other things being equal, a cut with a narrow kerf is a more efficient cut than one with a wide kerf. The better means of rating the oxygen efficiency appears to be in terms of the oxygen requirements per square inch of metal sectioned by the cut. Such a figure is frequently designated as the "specific oxygen requirement." The efficiency on this basis of good commercial cuts is approximately as follows:

Table 3—Specific Oxygen Requirements for Good Commercial Cuts

Thickness, Inches	Cu. Ft. Oxygen per Sq. In. Cut
1/2	0.04–0.07
1	0.06–0.11
2	0.08–0.15
4	0.11–0.20
6	0.13–0.25
12	0.20–0.40

The above figures merely apply to the cutting oxygen requirement. The figures will be increased by 0.01 to 0.03 if the oxygen for the preheating flames is included. This is on the assumption that the preheating gas is acetylene. If the preheating gas is hydrogen or city gas, or one of the liquefiable hydrocarbons, the figures may be increased by a greater amount.

The figures in the first column of Table 3 under "Cu. Ft. of Oxygen per Sq. In. Cut" are considerably less than those typical of the vast majority of cuts made in industrial establishments, but with a careful, painstaking operator who methodically studies his cutting operations, it is usually possible to very closely approach these figures in practice.

Figures on relative labor and overhead will, of course, need to be considered in addition to the figures on the oxygen consumption. Accordingly, a more detailed analysis of the operating variable will now be undertaken.

Temporarily ignoring all requirements for a cut other than that of a previously selected length of drag, it is obvious that so far as the labor and overhead costs are concerned it would in general be most economical to use the tip which will result in the fastest cutting. (This is on the assumption that a drag as short as the given standard length may be secured at the higher speeds.) However, if with increasing speed of cut-

ting the rate of oxygen consumption increases very much faster than the rate of cutting, while readjusting the oxygen operating pressure to maintain the standard length of drag, the economy in labor and overhead effected as a result of the higher speed could be entirely offset by the increase in oxygen cost.

By referring to Fig. 6 it will be seen that in cutting 6-in. material with No. 41 orifice an increase of cutting speed from 4 in. to $6^1/_4$ in. may be effected by means of an increase of only 16 to 20% in oxygen consumption. Hence, in this particular case the higher speed cutting is well justified. In general, however, it is not possible to realize as much of an increase of speed relative to the increased oxygen consumption. The relationship is generally that illustrated by Fig. 7 in which the operating speed and oxygen consumption for a given size of tip are indicated for two different values of drag.

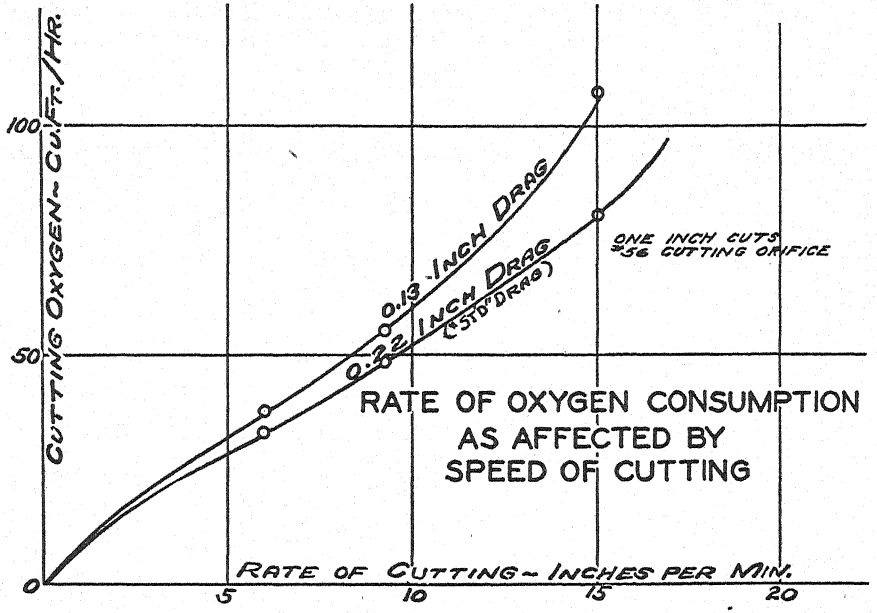


Fig. 7

Figure 7 indicates that for 1-in. cutting with a No. 56 orifice the cutting-oxygen rate of consumption increases almost in direct proportion to the speed of cutting (so long as only one size of tip is considered). Note, however, that the upper portions of the curves of Fig. 7 take on decided upward curvatures at the higher speeds, indicating that *the rate of oxygen consumption increases more rapidly than the rate of cutting* at the higher speeds. Incidentally, an appreciable departure from the proportionality relation always makes its appearance when the speed of cutting is so great that the minimum length of drag (as previously defined) for that speed is only slightly less than the length of drag selected as basic or standard. A careful consideration of the facts involved will reveal that this relationship

finds confirmation in a statement previously made in connection with Fig. 5, viz., that very short drags (approaching the minimum drag condition) may be obtained only at the price of a very considerable increase in the cutting oxygen.

By selecting typical figures for labor, overhead, fuel gas and oxygen costs it may readily be perceived that an operator may work well beyond the limit of proportionality and actually rather closely approach the speed at which the minimum drag is equal to the standard drag without running into uneconomical operations.

The foregoing has neglected the question of the quality of the cut. As the speed of cutting is increased the ultimate limit for a given tip may be imposed either by economic considerations alone or by the appearance of the cut. In the former case the tip is used at a speed great enough to cause the "minimum drag," characteristic of the given tip, to be almost if not actually as great as the length of drag selected as standard, and the operating pressure is set just low enough to obtain the standard length of drag. In the latter case speeds as high as this sometimes prove impracticable because of the tendency of the quality of the cut to deteriorate with increasing speed of cutting.

If the appearance of the cut is very important it is generally the controlling factor for cuts less than 2 in. in thickness. For intermediate thicknesses one or the other factor may prevail. For thicknesses over 6 or 8 in. there does not appear to be any substantial difference between the two different limits, and economical considerations alone may be employed in selecting the proper tip size, speed and operating pressure.

Tip Size

When the limiting speed (economic or otherwise) of a given tip has

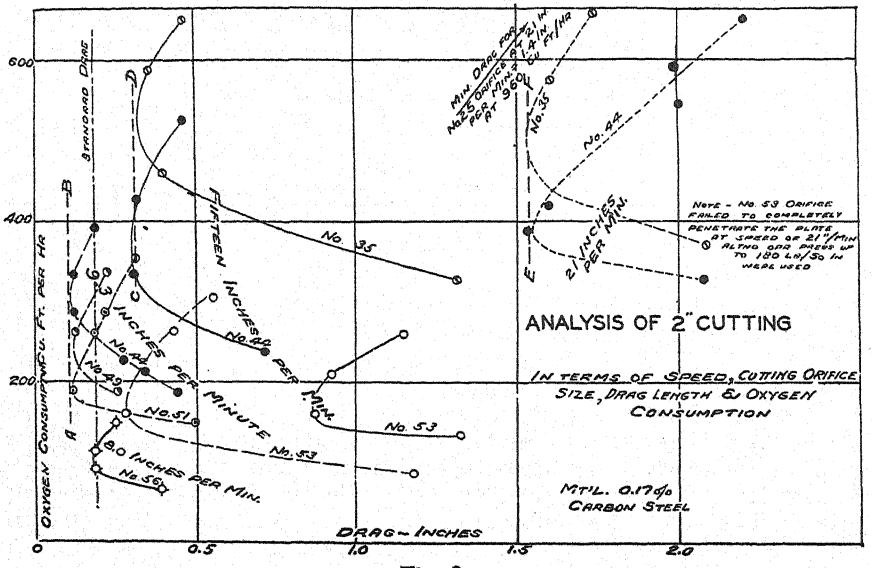


Fig. 8

been reached it is obvious that other sizes should also be systematically investigated. Another size of tip might afford even better results. Thus a larger tip might permit a much higher speed of operation, and consequently sufficiently decrease the labor, overhead and consumption of fuel gas to offset the increased oxygen discharge characteristic of the larger tip. A careful analysis of Fig. 8 indicates that there is no such tendency in the case of 2-in. cutting when a tip is operated at maximum efficiency as above described.

Since the use of the larger tip will only prove more economical than the smaller tip when the *saving in the cost of labor, overhead and preheating gas* (as a result of the decrease in the time required to execute the cut) is greater than *the increased cost of the oxygen used in the cutting jet* (as a result of the greater oxygen consumption of the larger tip), *the larger tip is justified when:*

$$\frac{\left(\frac{L}{S_1}-\frac{L}{S_2}\right)\left[C+\frac{G}{100}(g+RX)\right]}{60} > \frac{\left(\frac{LQ_2}{S_2}-\frac{LQ_1}{S_1}\right)\frac{X}{100}}{60}$$

(Saving in Gas, Labor and Overhead) (Increased Oxygen Costs)

In which

L = the length of the required cut in inches
C = hourly cost of labor and overhead in dollars
g = cost of fuel gas in dollars per hundred cu. ft.
X = cost of oxygen in dollars per hundred cu. ft.
G = hourly consumption of fuel gas in cu. ft.
R = gas ratio of preheating flames
S_1 = most efficient cutting speed of smaller tip in inches per minute
S_2 = most efficient cutting speed of larger tip in inches per minute
Q_1 = consumption of the cutting oxygen jet for the smaller tip in cu. ft. per hour
Q_2 = consumption of the cutting oxygen jet for the larger tip in cu. ft. per hour

From the above inequality it follows that:

$$C > \frac{(S_1Q_2 - S_2Q_1)X}{100(S_2 - S_1)} - \frac{G(g + RX)}{100}$$

For Acetylene Preheat $R = 1.1$ Approx. and

$$C > \left(\frac{S_1Q_2 - S_2Q_1}{S_2 - S_1} - 1.1G\right)\frac{X}{100} - \frac{Gg}{100}$$

As an illustration consider the curve shown in the lower left-hand corner of Fig. 8 for the No. 56 orifice and a speed of 8 in. per minute. This curve occupies such a position that its minimum drag practically corresponds with the standard drag for 2-in. cuts as defined in Table 2. Eight inches per minute and a No. 56 (drill size) cutting orifice therefore approximately represent the most efficient speed and tip size for cutting the particular 2-in. steel which formed the basis for the data of Fig. 8.

By interpolation it may be perceived that the proper speed of cutting for realizing the maximum tip efficiency of the No. 51 orifice is about 10 or 10.5 in. per minute. Hence;

$S_1 = 8$ and $S_2 = 10^1/_2$ Approx.

$Q_1 = 85$ and $Q_2 = 175$ Approx. (see Fig. 8)

$G < 13$

$$C > \left(\frac{8 \times 175 - 10^1/_2 \times 85}{10^1/_2 - 8} - 14.3\right)\frac{X}{100} - \frac{13g}{100}$$

$$C > 1.88X - 0.13g$$

The use of the No. 51 orifice would, therefore, only prove more economical than the use of the No. 56 orifice (assuming each is operated at its maximum efficiency) when the combined hourly cost of labor and overhead is greater than approximately the net figure obtained by deducting $^1/_8$ the cost of the acetylene (in dollars per hundred cubic feet) from twice the cost of the oxygen (in dollars per hundred cubic feet). Roughly, the hourly cost of the labor and overhead must be greater than $1^3/_4$ times the cost of the oxygen in dollars per hundred cubic feet.

The above example and the data of Fig. 8 are typical of high-quality steel of 2-in. thickness. For other conditions the results may be quite different, but in general it is true that larger tips are justified only if they result in more dependable or cleaner cutting. Although they do permit higher cutting speeds the gain is usually trivial as compared with the increased oxygen costs.

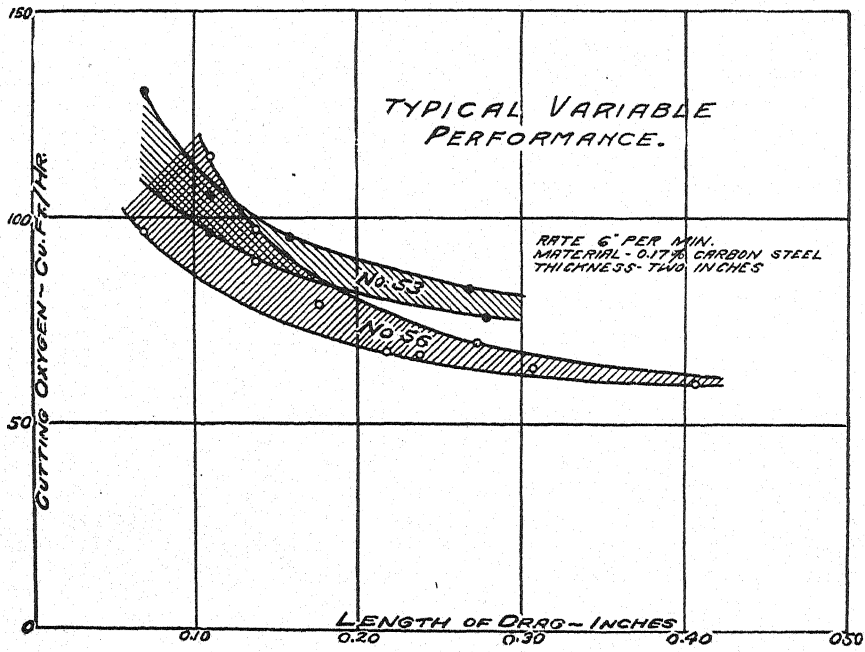


Fig. 9

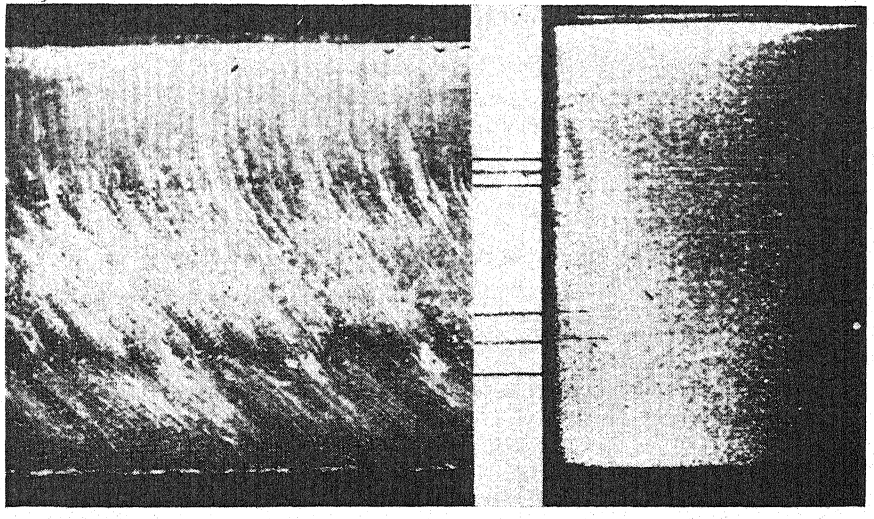
In actual practice, it is usually necessary to derive the cutting oxygen flow from the tip calibration and the pressure gage readings if one is to make use of computations of the type just illustrated. A calibration of the cutting tip may be obtained from the manufacturer of the tip, who can also furnish approximate values for the preheating consumption.

Another reason for avoiding excessive speeds is illustrated by Fig. 8. It will be observed that the lines *A-B*, *C-D* and *E-F* apparently define the minimum possible drags for speeds of 9.3, 15 and 21 in. per minute. Apparently no possible combination of tip size and oxygen rate of consumption (or operating pressure) will effect a shorter drag than this minimum. Hence, it is impossible to realize a sufficiently short drag if the speed is excessive.

Cut Quality

It sometimes happens that a given combination of cutting variables will not always give rise to a definite length of drag, but usually the variations in drag length are restricted within rather definite limits (see Fig. 9).

These variations from the normal length of drag are often traceable to variations in the quality of the material being cut. Apparently non-homogeneity of the physical structure of the steel is an important consideration. It would appear that where the drag-lines are of approximately normal shape but merely "off standard" sufficiently to introduce variations from the normal length of drag, it is merely a less serious case of the same phenomenon as is illustrated by cuts which are characterized by decidedly rregular drag-lines.



Section Normal to Face of Cut Prolonged Picric Acid Etch

Fig. 10—Discontinuity of Drag Lines

When the drag-lines are irregular, such as are illustrated in Figs. 10 and 11, a more serious condition is encountered in which it will be found that the faces of the cut are often badly grooved, concave or otherwise irregular. The condition represented by Figs. 10 and 11 is largely due to foreign inclusions rolled into the plate. Note the correspondence of level for these inclusions (see photo of etching) and the discontinuities in the drag-lines.

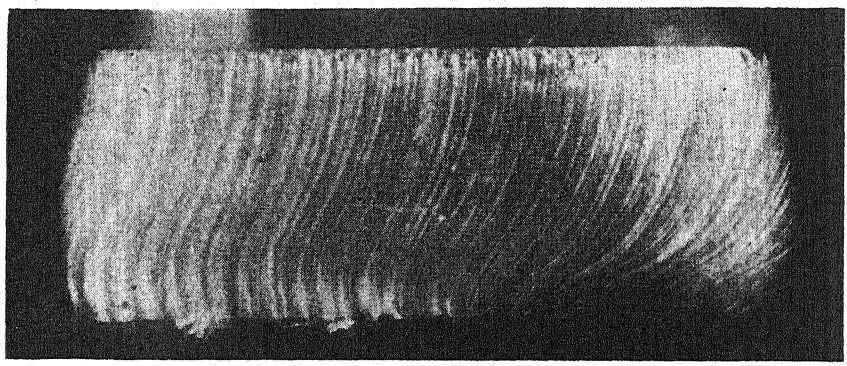


Fig. 11—Erratic Drag Lines

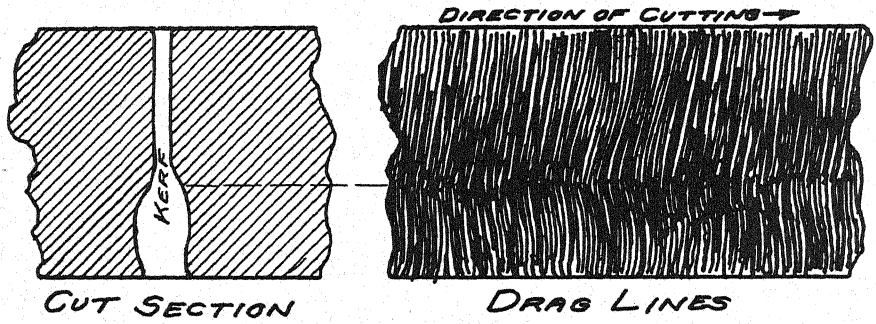


Fig. 12—Effects of Abnormal Disintegration in Lower Portion of Cut

In the case of cuts such as that of Fig. 12 non-homogeneity of material is not a sole controlling factor. This condition is apparently largely due to an abnormally turbulent or eccentric discharge from the tip. This sort of flow may be the result of roughness or mechanical defects in the throat or exit port of the cutting orifice or to adhering slag or scale on the end of the tip. However, such abnormal cuts may also make their appearance when a tip, which is apparently in normal condition, is used. In such cases the trouble may sometimes be overcome through the use of a lower speed of cutting and a lower operating pressure. A very high operating pressure is particularly liable to cause horizontal flutes (which are the result of flow nodes in the cutting jet).

The following is a list of the most important conditions which should be maintained in the interest of smooth cuts:

1. Uniformity of torch movement.
2. Uniformity of oxygen pressure regulation. (Important for heavy thicknesses and cold weather cutting.)
3. Uniformity of steel being cut.
4. Smoothness of bore and proper type of cutting orifice.
5. Cleanliness of orifice exit.
6. Sufficiently high oxygen purity.
7. Sufficiently low oxygen operating pressure.
8. A gradual increase of speed when starting the cut in very heavy thicknesses.
9. Sufficiently low operating speeds for light and moderate thicknesses.
10. Sufficiently high operating speeds for heavier thicknesses.

A word of explanation about items 9 and 10 appears essential. Excessive speeds are more commonly used than insufficient speeds in the case of light thicknesses (and the resulting cut quality is poor). However, it has been found that in the case of the greater thicknesses (over 4 in.) a ragged condition of the lower portion of the cut is sometimes encountered which is characterized by vertically disposed puckers, and which is due to insufficient speed. In increasing the speed, it will obviously be necessary to use a larger tip unless the change in operating speed is quite moderate.

Sharp upper edges of a cut are secured if the intensity of preheat is sufficiently low. In this matter, one must be sure that the preheat is sufficiently intense to break up surface scale and maintain the ignition point of the cut regardless of surface irregularities and heavy slag inclusions in the material near its surface. Moreover, the preheat intensity must not be so low that flying slag can readily obstruct the preheat orifices or give rise to backfiring.

Preferably, there should be no slag adhering to the bottom of the cut, and this is sometimes possible with the lighter thicknesses. A lightly adhering slag condition is favored by the following conditions:

1. Cleanness of cutting orifice exit.
2. Smoothness of cutting orifice.
3. A high purity of oxygen.
4. Scale or rust along the bottom edge of the material being cut.
5. Sufficiently high oxygen operating pressure (see Fig. 5).
6. Sufficiently large tip.

For cuts possessing drags much greater than what has been termed "standard drag" the consumption of oxygen becomes so low that the unoxidized iron content of the slag may be quite high. Such slag readily fuses to the lower portion of the cut. Usually, it has been found to be true that the higher operating pressures tend to give rise to less adhering slag and that frequently none at all will be obtained above a given pressure. As a general rule little is gained by exceeding the oxygen requirement for a standard drag in an effort to reduce the amount of adhering slag. The better procedure is to be sure that the tip is in satisfactory operating condition and to consider only those oxygen pressures that are required for the "standard" drags or whatever lengths of drag may be se-

lected as suitable. In extreme cases a larger tip may be employed than the most truly economical cutting tip if the slag condition is still unsatisfactory. When considering such a procedure one should be sure as to whether the increased cost of operating the larger tip would be justified as compared with the cost of slag removal by mechanical means. If one side of the steel is rusty it is better to turn the steel so that that side is lowermost. The slag does not adhere as tightly to rusty steel as it does to clean steel. On the other hand, the upper surface of the steel should be as clean as practicable in order to minimize the preheat requirement.

Precision

Where the torch is held rigidly and advanced at constant speed, as in machine-guided oxygen cutting, across-the-cut tolerances may be maintained within narrow limits. In ordinary steel of 6-in. thickness, cut surfaces can be held true, as to cross-sectional squareness, within $^1/_{32}$ in. Cuts in thinner sections can be held within proportionately smaller limits. The degree of longitudinal precision of a machine-guided torch cut depends on the trueness of the guide rails of the cutting machine, the clearances in the operating mechanism and the regularity of the propelling unit. Machine-guided torch cuts are frequently so smooth and square and have such sharp edges that they require no further finishing of any kind.

The squareness and planeness of cut faces depend to a considerable extent upon the operating pressures employed. For best results the operating pressures for smaller sizes of tips should not exceed 30 lb. and for medium sizes of tips, that is, tips suitable for thicknesses up to 8 in. or 10 in., the operating pressure should not exceed 40 lb., provided flat cut faces are actually required. This is upon the assumption that the hose lines and approach passages of the torch are adequate in the case of the heavier gas flows.

It is impossible to attempt high precision shape cutting without an accurate knowledge of kerf widths. It is not practicable, however, to present data on kerf widths in this particular treatment because the widths not only vary considerably with the operating pressure, speed of cutting, etc., but are primarily dependent upon the particular cutting orifice employed. It is therefore advisable that such information be gained by direct observation. Care should be taken not to generalize such data because kerf widths are specific to the particular cutting conditions involved. For example, if will be found that the kerf is affected by the distance of the tip from the upper surface of the material. The tendency is for wider kerfs to result when the tip separation is increased, but if the operating pressures are maintained within the range above specified, this effect will be almost, if not entirely, negligible.

Precision shape-cutting also demands that attention be given to the question of thermal expansion. Lack of precision may result either from warpage of the material in event that thin sheet or plate stocks are involved, or it may result from a shifting of the plate during the progress of the cut as the result of the heat of the cutting operation. One should, therefore, carefully plan the operation so as to minimize these effects. For instance, it is desirable to eliminate, if possible, narrow sections of metal that may become overheated.

Oxygen Purity

The importance of high purity oxygen for cutting operations is well recognized today, but the effect of extremely small percentages of impurities is so serious that it needs to be emphasized that one should make certain that only the very highest purity oxygen is used. The pernicious influence of what might otherwise be regarded as trivial amounts of

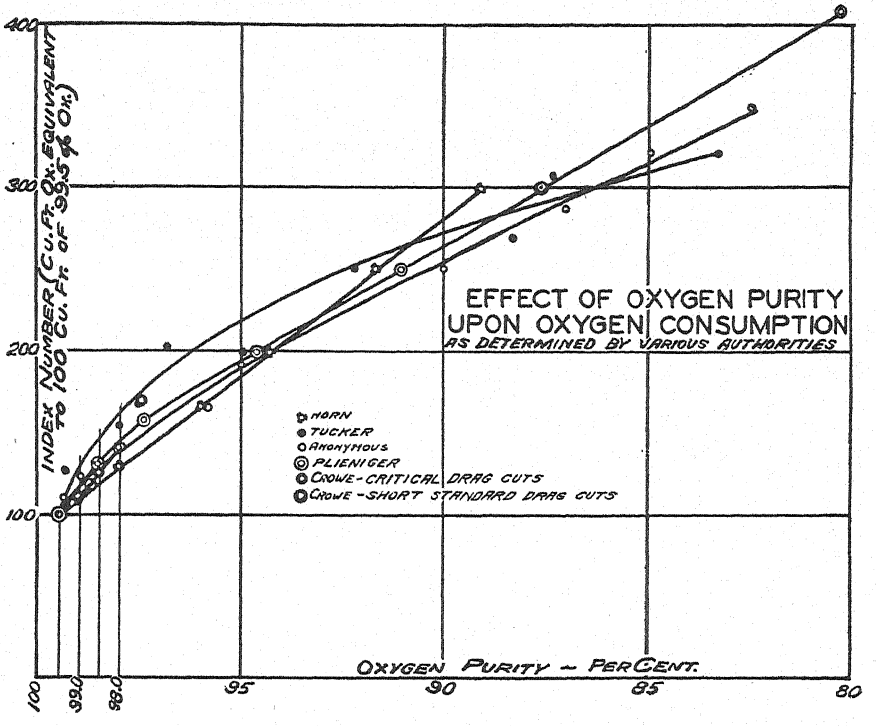


Fig. 13

impurities is illustrated by Figs. 13 and 14. It will be observed (see Fig. 13) that the decrease of oxygen purity from 99.5 to 98.5 will on the average necessitate an increased oxygen consumption of about 25%. The fact is that the oxygen cutting of steel involves one of those chemical processes which is self-propagating but in which there is not a great deal of heat developed in the reaction at any given point beyond what is necessary to raise adjoining regions to the kindling temperatures. It is typical of such reactions that small changes in concentration, or purity, of one of the constituents, result in very great variations in the speed of the reaction.

Fuel Gases for Oxygen Cutting

Several different fuel gases are used for oxygen cutting torches, the selection being largely the result of economic considerations. It is essen-

tial, however, that the torches and tips used be designed primarily for the particular fuel gas to be used, if the best results are to be obtained.

Essentially the function of the preheating flames is twofold. On the one hand, in starting the cut enough heat must be supplied at the upper forward corner of the steel to rapidly heat the steel to the ignition temperature. This temperature is usually estimated at approximately 1600°F On the other hand, during the actual cutting operation enough heat must be transmitted to the upper surface of the steel to maintain the thermobalance as explained in the section on "Chemistry of Oxygen Cutting," (page 656), and to dislodge or greatly reduce the thickness of any heavy rust, scale or paint.

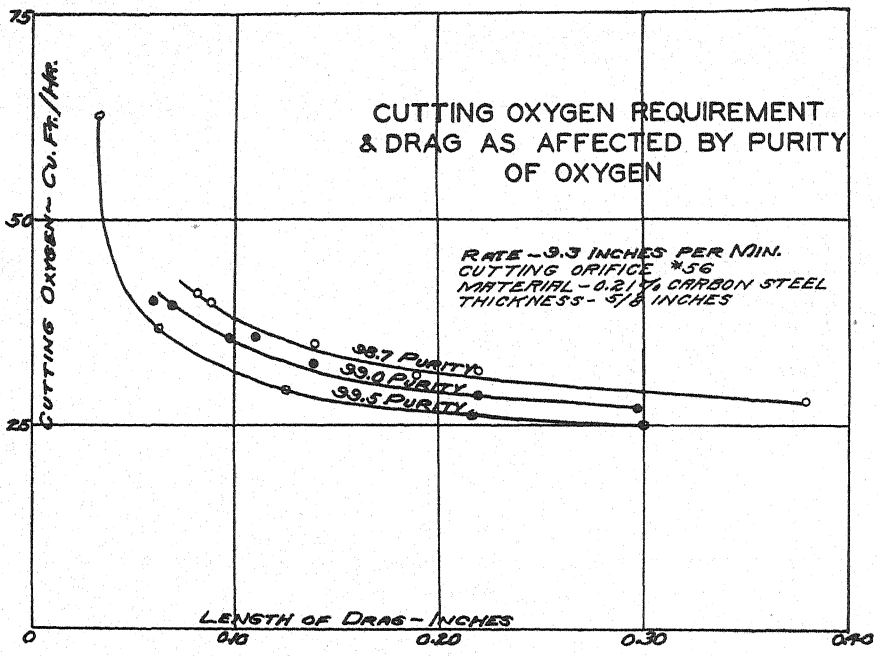


Fig. 14

A preheat intensity which is sufficient to rapidly raise the steel to the ignition temperature will also be sufficient for rapid and highly economical cutting. The expression "preheating time" merely signifies the time required to heat the steel to the ignition temperature; that is, to a temperature sufficiently high that, when the oxygen cutting jet is directed onto the heated locality, oxidation will be initiated and the cutting operation will begin.

Acetylene.—At present this gas is the most widely used fuel gas in oxygen cutting. Its chief advantages are availability, high flame temperature and wide-spread familiarity with its flame characteristics. The high flame temperature is particularly important when the starting time (such as for short cuts) is an appreciable fraction of the total time for cutting.

Hydrogen.—At present hydrogen is preferred for underwater cutting and is

claimed to have advantages for heavy cutting because of the long flame. Its disadvantage is its relative low Btu. value per cubic foot of gas.

Propane.—This gas is being used regularly in a number of establishments because of its relatively low cost and high Btu. value per cubic foot of gas.

City Gas.—City gas has been widely used in a few industrial regions, notably the west of Scotland, where economic factors were favorable. Because of the lower flame temperature oxy-city gas cuts in thin materials are likely to be smoother and sharper than oxyacetylene, according to a number of writers. The speed of cutting with city gas as compared with acetylene has been found to be somewhat slower by most authorities. Low calorific value and low flame temperature account for the high consumption of city gas in oxygen cutting.

With the exception of acetylene and propane the usual fuel gases involve a mixture of several constituents.

Heavy Cutting

The question of variations in the quality and homogeneity of the steel is a troublesome one when cutting heavier thicknesses. With very heavy thicknesses it appears to be a matter of real economy not to risk a very bad or incomplete cut merely in order to attempt ideal economy. The goal must be approached cautiously for if economy of gas and labor is overemphasized, there is a very real danger of ruining expensive pieces of steel. Nevertheless, when doing much cutting in any given thickness, a careful operator will be able to materially improve the economy of the operation over what is obtainable with the cutting conditions specified by a cutting guide such as Table 1.

In cutting heavy thicknesses considerable skill must often be called into play in starting the cut if the initial lower corner is to be completely severed, or if the cut is not to be ruined by pocketing of the cutting stream in the lower portion of the cut. It is quite essential that the front edge of the piece being cut be very clean. This especially applies to the lower portion of the front face. The axis of the tip should be carefully aligned with the front edge of the material. This is best accomplished by turning on the oxygen cutting jet while the preheating flames are burning and with the axis of the tip displaced about $^1/_4$ in. from the forward edge of the work piece. The cutting jet, under these conditions, will be rendered sufficiently visible so that if it is not parallel to the forward face the fact will immediately be apparent, and the torch may be readjusted accordingly. It is important that the jet be either parallel to the forward face or else "toed" in very slightly, i.e., a trifle closer to the bottom edge than to the upper edge. If it slopes backward the slag that flows downward over the lower portion of the forward face will not be blown clear by the force of the jet and it may have an opportunity to freeze so that as the jet moves forward and the cut progresses both forward and downward the cutting action near the lower edge will ultimately be resisted as a result of the protective action of the slag. If the jet is toed forward too much it may be deflected from the forward face so that the result will be much the same as if it sloped backward.

In starting the cut the movement of the torch should be delayed or retarded just long enough to allow the cutting stream to actively attack

the metal throughout nearly the entire depth of the material before the torch is permitted to proceed normally. The ideal method is to either intermittently start and stop the machine which carries the torch or to so greatly reduce its speed that practically the entire forward face of the material along the line of the desired cut may be actively attacked by the cutting stream with the least possible forward travel of the torch. If the forward movement is almost stopped, however, it will be found that the cut will cease to propagate either forward or downward. Any tendency, therefore, for the oxidation activity to weaken generally, must be met by an increase of speed. Any tendency of the forward action to proceed faster than the downward action must be met by a reduction in speed. If the retardation is too much or if in any other manner a mass of slag is permitted to freeze near the bottom of the front edge of the material on the line of the cut so as to protect the adjacent metal from the action of the cutting stream, an uncut forward corner or even a bad pocket and consequent failure of the cut may result. If the piece is very heavy it may even prove worth while to heat the lower portion of the front face with a large welding flame.

For unusually heavy pieces it is sometimes desirable to undercut the forward edge of the material by means of a hand torch. Usually, however, a reasonable amount of skill and attention to details will make undercutting unnecessary. If used, undercutting should be done judiciously. If done by an inexperienced hand it may prove ineffective, or exceedingly ragged cuts may be obtained.

Considerable skill is also often required in completing the final corner of heavy cuts. A slight retardation of the movement of the torch is desirable at this point as at the beginning of the cut, but the retardation must be carried out with care or otherwise it will be worse than useless. Of course, it is sometimes possible to eliminate the necessity for great care in beginning and completing the cut by using a *greatly* oversized tip and deficient speeds and thereby wasting much oxygen, but it does not appear advisable to derive cutting conditions for heavy thicknesses on such a basis when with a little care the economy of cutting can be greatly improved through the use of a somewhat smaller tip.

If the speed is too low, the lower portion of the cut is likely to be quite ragged. Again, if the tip is too small no amount of skill will prevent an uncut corner or bad pockets at the start of the cut.

Where the nature of the cutting machine and the type of work involved permit, the angle of incidence of the cutting stream as it enters the upper edge of the cut may be changed as indicated by Fig. 15 so as to facilitate the completion of the final corner of the cut. Note, however, that the change in the angle subtended by the drag-lines is relatively small as compared with the change in the angle of incidence. The advantage to be derived by this procedure, however, may be offset by the unfavorable effect upon the appearance of the cut and the possibility of "losing the cut" entirely as a result of disturbances caused when altering the angle of incidence. Again, if the change of the angle of incidence is too great, the uncut final corner will be greater than if the angle of incidence is normal, viz., 90°.

Inasmuch as the final corner of a cut may be more readily severed by

tilting the torch, as just mentioned, it would seem that the oxygen operating pressure and incidentally the corresponding oxygen consumption necessary for the execution of a cut of given drag length could be diminished, but careful measurements have indicated that the practical advantage to be gained in this manner is generally quite negligible.

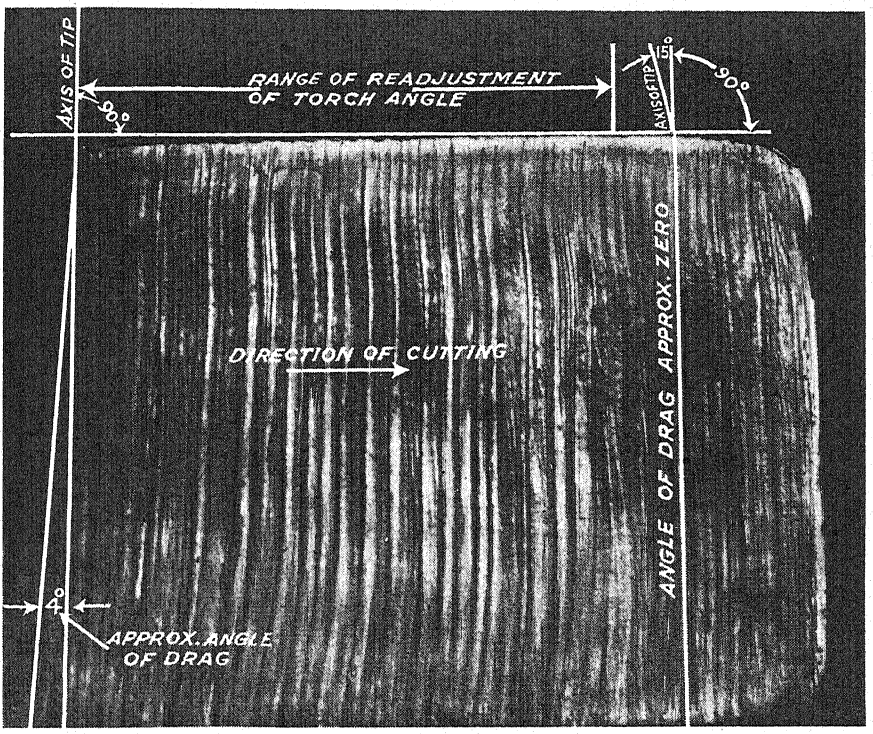


Fig. 15—Effect of Varying the Angle of Cutting Incidence

The greatest care must be exercised in choosing the operating pressure in the case of heavy cuts. Not only is the range of suitable pressures considerably narrower for the heavier cuts but the pressure drops through the hose line connections and the torch increase rapidly with the increasingly heavy flows demanded for heavy cutting. Variations in the quality of the steel are also more important in the case of heavy cutting. The result is that frequently even an approximate operating pressure may not be definitely predetermined unless the precise torch, hose line and connection fittings, as well as the exact nature of the steel, are known. In order to eliminate the excessive pressure drops often encountered in heavy cutting, larger hose ($^3/_8$ in. or even $^1/_2$ in. size) with correspondingly larger hose glands, and a machine torch with larger approach passages and cutting valve are often used. With such equipment it is frequently possible to reduce the necessary operating pressure by 30 to 50%. Nevertheless, failure to cut heavy material successfully may sometimes be traced

to the use of larger hose lines, glands, etc., and a failure to correspondingly reduce the operating pressure. It should be emphasized that with suitable equipment successful cutting of 12-in. material has been made with operating pressures as low as 60 to 70 lb. The thought which needs to be impressed is that more failures in heavy cutting result from excessive pressures than from deficient pressures.

Metallurgical Effects of Oxygen Cutting

As explained previously, a considerable quantity of heat is liberated in the kerf when steel is cut with the oxygen jet. Much of this heat is transferred to the walls of the kerf and as a result the metal for an ap-

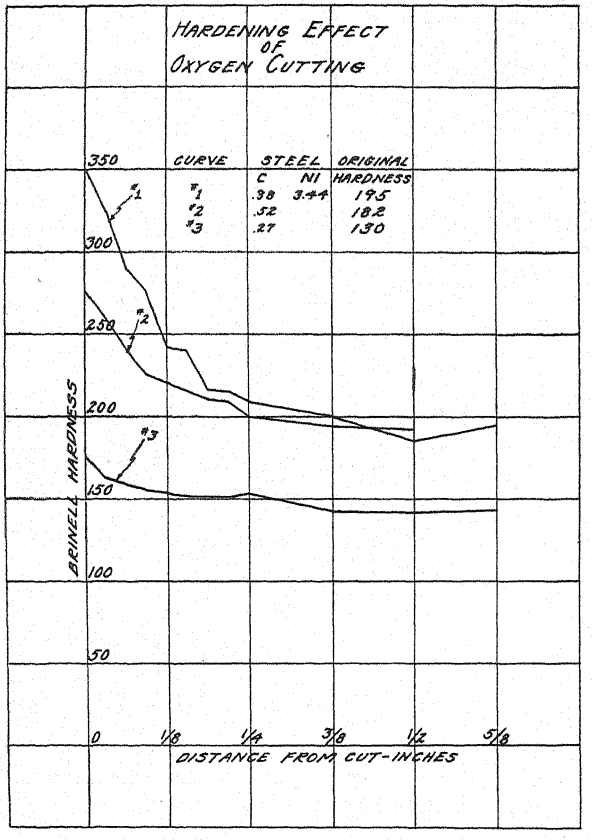


Fig. 16—Surface-Hardening Effect ($6^1/_2$-In. Billets)

preciable depth adjoining the cut surface is heated rapidly to a temperature well above the critical range. But as the cut progresses and the source of heat moves on, the mass of cold metal near the cut acts as a quenching medium and rapidly cools the heated metal. The phenomenon is in some respects similar to that of the usual heat-treating operation.

A piece of steel, heated to above the critical temperature range and rapidly cooled, will harden and the degree of hardening will depend to a large extent on the amount of carbon and alloying elements present in the steel, and also on the rate of cooling. A rapid quench from a high temperature will result in a hardened steel. This is the condition brought about at the face of the cut where the temperature of the cutting operation has been high enough to raise the metal well above the upper critical or A_3 transformation temperature and where this zone is bounded by large masses of relatively cold metal.

A study of Fig. 16 brings out four important facts:

1. The temperature necessary for hardening penetrates to a measurable distance. In this particular instance to approximately $^1/_8$ to $^3/_{16}$ in.
2. The higher carbon and alloy steels are hardened to a greater degree than the lower carbon and unalloyed steels.
3. The hardening effect on carbon steels containing 0.30% carbon or less is negligible for most practical purposes.
4. The hardness effect progressively decreases away from the cut.

A metallographic examination of the hardened area shows that for the lower carbon steel the pearlitic structure normal for most steels in the annealed state has been converted into sorbite (or into troostite if the carbon content is high enough), and that the same constituents with the addition of martensite are obtained in the case of the higher carbon and alloy steels. Moreover, as illustrated by Fig. 17, the zone intermediate

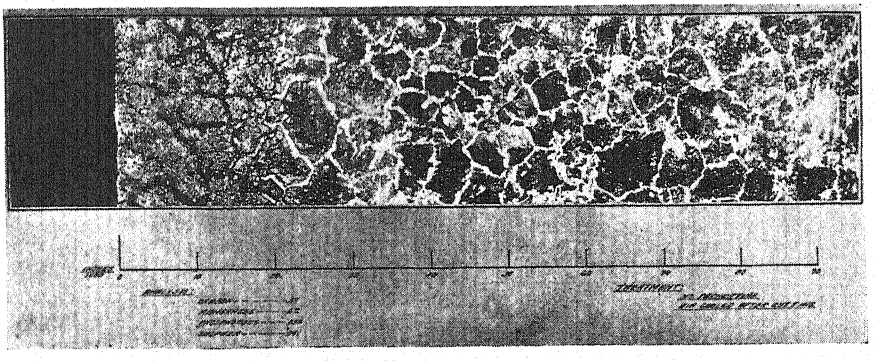


Fig. 17—Effect of Oxygen Cutting on Microstructure

between the face of the cut and the unaffected metal at a distance from the cut reveals more or less of the original grain structure. The obvious explanation is that the metal was not held sufficiently long at temperatures above the transformation temperature to permit complete transformation to austenite. It is because the austenitic transformation was incomplete that it was not possible when the metal was subsequently chilled to fully develop the sorbitic and troostitic structures. This is probably the primary explanation for the progressively decreasing hardness inward from the face of the cut, although some increased hardness at the face of the cut may be due to the fact that the quenching is from a higher temperature.

It has been clearly shown that the effect of oxygen cutting does not

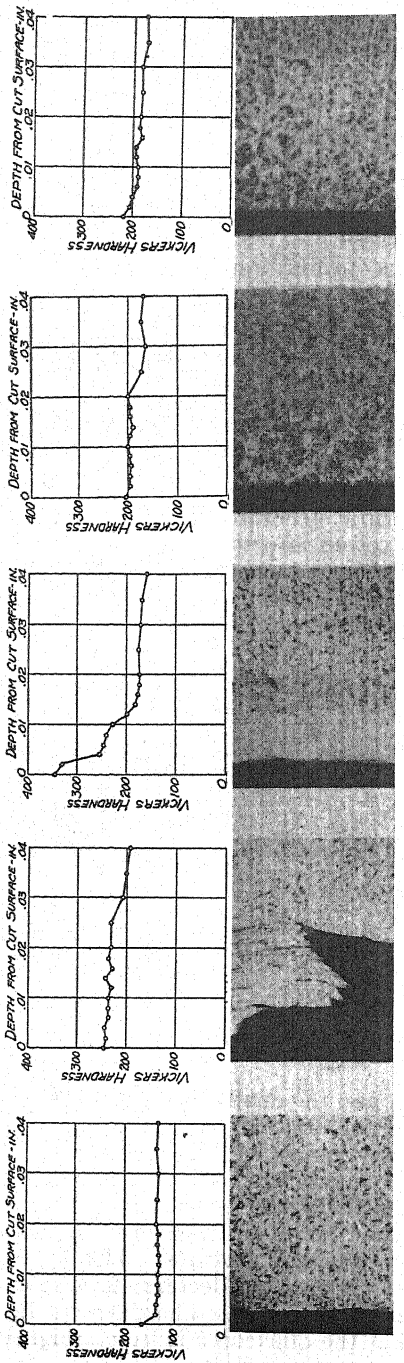


Fig. 18—Effect of the Five Cutting Procedures on the Surface Hardness and Microstructure of the Test Plate

(J. H. Zimmerman, *Mechanical Engineering*, 1935)

extend to a very great depth. With thicknesses as great as 30 in. it extends to a depth on the order of $^3/_8$ in. However, as indicated by Fig. 16 the depth of hardening for 6-in. cutting is only about $^1/_8$ in. with low carbon steel (although it may be as much as $^1/_4$ in. with higher carbon and alloy steels). For $^1/_2$-in. material the depth of the affected zone in low carbon steel is only about $^1/_{32}$ in. (see Fig. 18). For lighter thicknesses it is even less. If actually required, much or even all of the hardened metal may readily be removed by machine tools. If a machine finish is not necessary, however, and the cutting has been done with sufficient accuracy the affected metal need not be removed, except possibly in the case of the higher carbon steels and alloy steels. Bending and tensile tests made with specimens prepared from steel of the structural type containing less than 0.30% carbon, by oxygen cutting, shearing, friction sawing, etc., have shown the damaging effect of the latter two methods is generally far more pronounced than when oxygen cutting is used.

Figure 18 gives some indication of what may be expected with $^1/_2$-in. steel that has been sheared, friction sawed or machined as compared with typical examples of oxygen cutting. It will be seen that the oxygen-cut edge is in much better condition than that produced either by shearing or friction sawing. Metallographically it is superior to the unaffected metal or the machine-cut edge because it is characterized by the relatively tough sorbitic structure which has characteristics superior to pearlite, the prevailing constituent in annealed or air-cooled steels of the low carbon type.

Because it has now been shown that for lower carbon steels there can be no question that the oxygen-cut surface is at least equal in physical properties to the unaffected metal, the A.S.M.E. Boiler Code Committee has removed restrictions on the welding of surfaces prepared by the oxygen cutting process. It merely specifies that "the edges must be uniform and smooth and must be freed of all loose scale and slag accumulations before welding." It furthermore states that "The discoloration which may remain on the flame-cut surface is not considered to be detrimental oxidation." The Boiler Code does not, however, permit welding oxygen-cut surfaces in steel of over 0.35% carbon content. This is because with the higher carbon content there is a tendency for the cut edge to develop minute cracks. The proper means for overcoming this condition will be treated in a later section of this article.

Chemical Changes

In addition to the purely metallurgical changes there are chemical changes which extend to a depth as great as $^1/_8$ in. Samples taken from near the surface of carbon steels show a higher carbon content than samples taken at a greater depth. The increase in carbon near the surface occurs regardless of whether the preheating flames are fed by a gas containing carbon, such as acetylene or by a carbon-free gas, such as hydrogen. It would appear that the increase in carbon is brought about, at least in part, by migration of carbon from the colder metal to the hotter metal. Several investigators have found that the carbon content is actually lower a moderate distance in from the face of the cut than it is in the unaffected zone at a distance from the cut (see Fig. 19). It appears logical, therefore, to con-

clude that the increased carbon content at the face of the cut may have been derived from the region of abnormally low carbon content. A carbon migration toward the face could presumably be the result of carbon enrichment effected by the progressive precipitation of ferrite which advances from more remote regions toward the face of the cut because of the higher temperatures attained closer to the cutting zone.

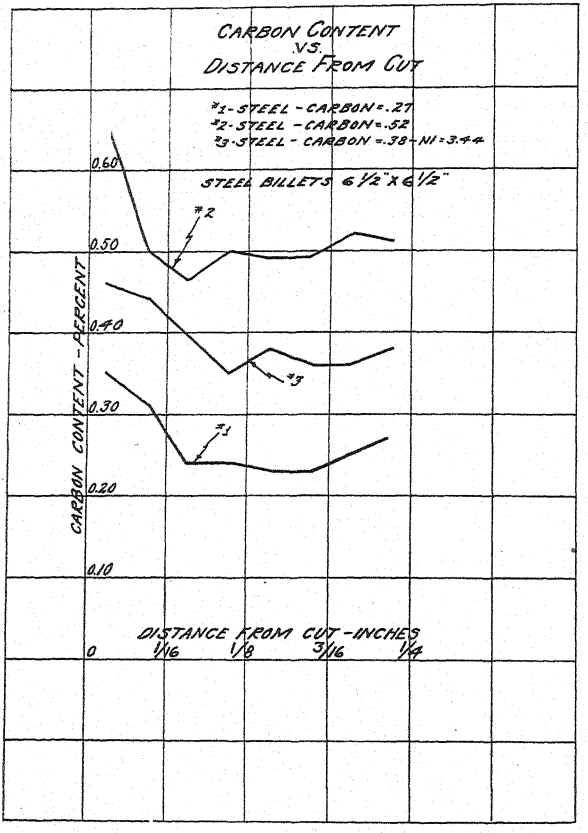


Fig. 19

There are, however, two other possible explanations. One is that some carbon may be absorbed from the hot metal being oxidized in the cut. The other is somewhat similar, viz., that the action of the oxygen jet at the face of the cut is such that the ferrite is more actively attacked than is the cementite and that the increased carbon content is derived from the latter. This, however, is probably only a minor factor.

Nickel acts similarly to carbon in concentrating at the surface of the cut; chromium and copper act oppositely, while manganese and silicon are not appreciably affected.

Effects of Alloying Elements

Alloying elements have two possible effects; first, they may increase the resistance of the steel to cutting and, second, they may give rise to harder cut surfaces. The first effect may roughly be judged by the following notes, which have been derived from many different sources, the reliability of which has not in all cases been verified.

Where an alloy steel is difficult to cut by other means, it will be found that a decided improvement is effected by tightly clamping a "waster" plate to the upper surface and cutting through both thicknesses. Another method is to weld a heavy bead on the upper surface along the proposed line of cut. Frequently, steels which cannot be oxygen cut by any other method may be cut by means of such artifices.

Table 4

Element	
Carbon C	Steels up to 0.30% carbon can be cut without difficulty. Higher carbon steels should be preheated to about 600°F. to prevent hardening. Graphite and cementite (Fe_3C) are detrimental but cast irons containing 4% carbon may be cut by special technique (see p. 692 et seq.).
Manganese Mn	Steels up to 14% manganese and 1.5% carbon are cut with difficulty and for best results should be preheated.
Silicon Si	Silicon in amounts usually present has no effect. Transformer irons containing as much as 4% silicon are being cut. Silicon steel containing considerable amounts of carbon and manganese must be carefully preheated and post-annealed for best physical properties.
Chromium Cr	Pure chromium reacts with oxygen only when at very high temperature. Steels up to 5% chromium are cut without much difficulty when the surface is clean. Higher chromium steels, such as the 10% chromium steels, require special technique and the cuts are rough. In general, carburizing preheating flames are desirable when cutting this type of steel.
Nickel Ni	Amounts up to 20% or 30%, if the carbon is not too high, may be cut. Up to about 7% nickel content, cuts are very satisfactory.
Molybdenum Mo	Affects cutting about the same as chromium. The pure metal is difficult to cut. Aircraft quality chrome-molybdenum steel offers no difficulties. High molybdenum-tungsten steels, however, may be cut only by means of special technique.
Tungsten W	The pure metal may be cut, if heated to a sufficient temperature. The usual alloys up to 12% or 14% may be cut very readily, but with a higher percentage of tungsten, cutting is difficult. The limit seems to be about 20% tungsten.
Copper Cu	In amounts up to about 2%, copper has no apparent effect.
Aluminum Al	Unless present in large amounts (on the order of 10%), the effect is inappreciable.
Phosphorus P	Has no effect up to amounts tolerated in steel.
Sulphur S	Small amounts, such as are present in steels, have no effect. With higher percentages of sulphur, the rate of cutting is reduced and sulphur dioxide fumes are noticeable.
Vanadium Va	This alloy in small amounts may improve rather than interfere with cutting.

Heat Treatment

Plain carbon steels containing 0.30% carbon or less are not, as a rule, sensitive to sudden changes in temperature, neither do they become very

hard when heated and quickly cooled, and these steels may usually be successfully oxygen-cut without taking any special precautions. As the carbon increases or alloys are added, steels become more and more responsive to heat treatment, that is, they become harder when suddenly cooled from above the critical range. Being harder, they are more brittle and more liable to crack from strains set up by cooling stresses. It is therefore advisable to preheat this latter class of steels before flame cutting. In fact, for carbon content over about 0.50% and for chrome-alloy steels preheating should always be resorted to.

The need for preheating is greater for the heavier sections than for the lighter sections and becomes a requirement when heavy sections of a high carbon or alloy steel are to be cut to intricate shapes. With such shapes having acute angles where high stress concentration will be involved, it is particularly desirable to preheat.

Preheating accomplishes several useful purposes:

1. Preheating increases the efficiency of the flame-cutting operation by reducing the amount of oxygen required to make the cut.
2. It reduces the temperature gradient set up by the cutting operation. This in turn reduces or gives more favorable distribution to the cooling stresses and, thereby, prevents the formation of quenching or cooling cracks.
3. It reduces the hardness of the cut surface by reducing the rate of cooling.
4. It reduces the carbon and nickel migration toward the cut face by lowering the temperature difference between the cut face and the body of the metal.

In practice the temperature used for preheating varies from a few hundred degrees to about 1300°F. The preheating temperature most employed ranges from about 600°F. to about 1100°F. The tendency among those who have had much experience in this direction appears to favor the lower temperatures (not greatly in excess of 600°F.) rather than the higher temperatures. When the temperature is too high, particularly if it exceeds 1200° or 1300°F., it is difficult to make smooth cuts. The higher the temperature, the more rapid is the reaction of the oxygen with the iron; it is, therefore, possible to cut faster when the metal is preheated. But it is essential that the temperature be fairly uniform, for if the outside of the metal being cut is at a lower temperature than the interior, the oxidation reaction will proceed more energetically in the interior than at the top and bottom. The result is often the formation of large pockets in the interior that will either give rise to an unsatisfactory cut or to such slag pollution at lower levels that it will be impossible for the oxygen stream to completely penetrate the steel. Consequently, it is important that the cutting be effected as soon as possible after the material is removed from the preheating furnace; otherwise, the surface may become chilled.

If, through lack of facilities, preheating should prove impracticable the stresses incident to cutting may be reduced appreciably in the case of very light cutting by passing the cutting torch with the preheating flames lighted and the cutting oxygen turned off, slowly over the line of cut until the metal in this region is raised to the approximate temperature desired. While one such pass may suffice, two or more passes generally yield better results. Another method which gives even better results is to preheat the metal by means of a special multi-flame heating tip so mounted as to precede the cutting tip.

If immediately after the cutting operation is completed the piece cut is heated to a temperature of 1100° or 1200°F., the internal stresses left after cooling will be practically eliminated and the brittle constituents, martensite and troosite, which may be present in the higher carbon or alloy steels, will be converted into sorbite or similar spheroidized structures, either of which is very ductile. If the temperature of heating is above the critical range of the steel (usually about 1450° to 1550°F.) all traces of the metallurgical changes caused by the oxygen cutting will be eliminated. If a furnace is not available or because of size it should prove impracticable to use a furnace, the cut surface usually may be reheated to the proper temperature by means of multi-flame heating tips.

Multiple and Stack Cutting

Oxygen cutting is not necessarily restricted to a single torch per operator. In many applications of machine cutting as many as six torches are used to cut a like number of identical shapes simultaneously, thereby effecting considerable economies. Cutting by this method is greatly facilitated by making use of a central control station for controlling the gas and oxygen supply to each of the torches. Concentric circles for flanges and the like often are cut in one operation, with two or more torches.

In addition to cuts made through a single thickness of material, oxygen cuts are made through several thicknesses simultaneously (see Fig. 20). This operation is known as "stack cutting" and offers a means of cutting

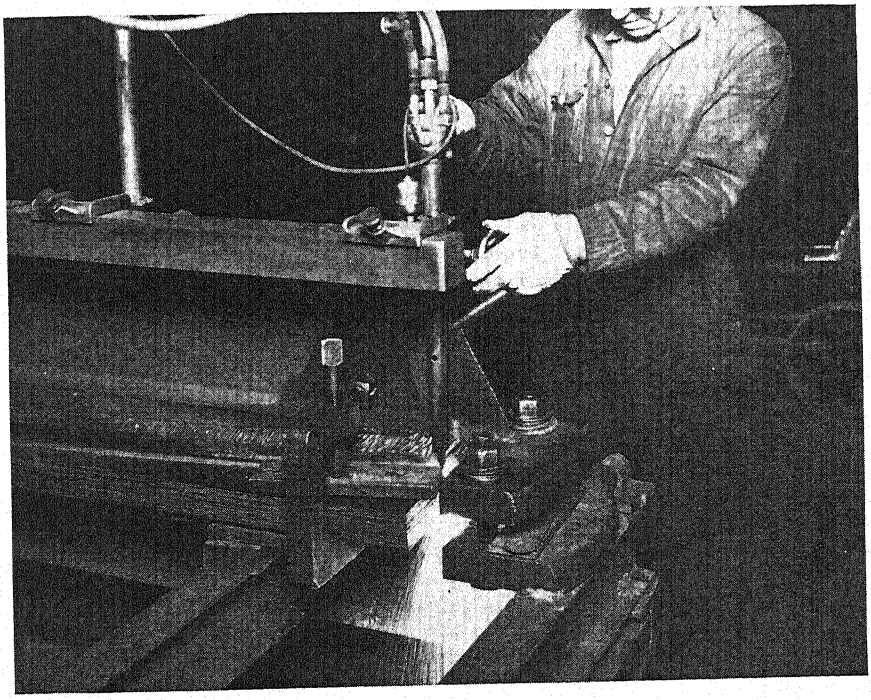


Fig. 20—Stack Cutting

a number of shapes simultaneously with a single torch or blowpipe, instead of employing multiple torch cutting. While not widely employed at present, this process may be utilized with success and economy under certain conditions of material, thickness, assembly, cut quality, dimensional tolerances and cost of setting up the work.

The plates in the stack should be clean and flat, with edges in alignment where the cut is started. The number should vary with the thickness of individual plates, to keep stack thickness within proper limit.

It is essential that all of the sheets or plates in the stack be in intimate contact if acceptable cuts are to be obtained. To insure good contact the general practice is to use some form of clamping device for bringing the plates together along the line of the cut. Owing to thinness or compositions of some sheets it sometimes may be found difficult to maintain the cutting reaction. As an aid in preventing the loss of such cuts use is often made of a "waster" plate. This plate is placed on top of the stack. It should be of a composition that can be readily cut and of sufficient thickness to prevent the preheating flames of the torch from melting the edges of the uppermost sheet in the stack.

Lance Cutting

The oxygen lance affords a method which may be employed for cutting any of the steels which may otherwise be cut only with extreme difficulty or not at all. Ordinarily, the lance is simply a length of black iron pipe fitted with a valve at one end to which an oxygen hose is connected large enough to supply oxygen at a high rate of delivery from a bank of oxygen cylinders equipped with a pressure-reducing valve of suitable capacity. A typical oxygen lance is illustrated by Fig. 21. It is not necessary as a rule that the pipe be very large; in fact, even for quite heavy operations a pipe of $^1/_4$-in. nominal pipe size is usually sufficient. In extreme cases a pipe of $^3/_8$-in. size may be employed.

In order to start the operation it is first necessary to preheat the edge of the steel, if a straight line cut is to be executed, or a highly localized region if a hole is to be pierced. For this purpose an oxyacetylene torch with a large size welding tip is usually employed. When the steel has been raised to a bright red heat, the end of the lance is brought against the heated area and with the operator at a safe distance and amply protected against flying particles of steel and slag, the oxygen lance valve is opened. Oxygen at pressures not to exceed 75 or 100 lb. psi. is then directed against the heated area of the steel. Sufficient heat is liberated through the combustion of the end of the lance, which has been ignited by the preheated portion of the work piece, to continue the propagation of the cut and to permit oxidation of the steel of the work piece. Such oxidation might not otherwise be possible because of the greater heat-input requirement for cutting such steel.

The end of the lance is so held in the cut or hole that the cutting oxygen stream emerges in such a direction as to enlarge the cut or hole in the manner desired. The lance, of course, is slowly consumed during the operation, so that if the operation is greatly prolonged it is necessary to replace the lance pipe with a new length of pipe from time to time. Accordingly, and in order that the cut be not lost during change of lances, replacement lances should be immediately available. In some instances it is desirable to use

extra heavy steel pipe or pipe loaded with steel rods or wires in order to render the reaction more vigorous. In most instances, however, the simpler arrangement will be adequate.

Oxygen lance cutting is useful for piercing holes in heavy thicknesses of steel preparatory to removing a block of steel by ordinary shape cutting

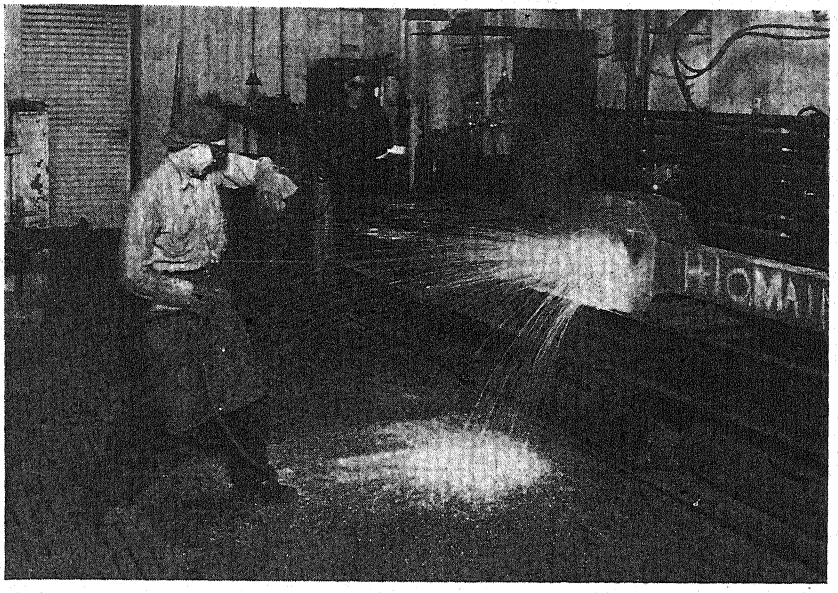


Fig. 21—Lance Cutting

operations. Thus in Fig. 21 the lance is being used to pierce a hole in the end of a main connecting rod forging in order that the machine cutting torch may subsequently be able to start the interior cut successfully, which cut will be required in order to remove the circular block of steel. Although cutting tips are sometimes used for piercing operations, if the plate is more than 2 in. in thickness it is highly desirable to use the lance in order to avoid the possibility of damaging the cutting tip during the piercing operation. Wherever possible the piece being cut should be turned so that the slag and molten metal may flow out of the cut by gravity. High oxygen pressure should not be relied upon to blow them out.

The oxygen lance has also been used successfully for the cutting of very heavy thicknesses of steel which are difficult to cut merely because of the great thicknesses involved. Thus, thicknesses on the order of 30 in. and upward have been handled successfully either by means of the lance alone or by means of the lance inserted into a cut opened by a cutting torch carried by a cutting machine, the lance following immediately behind the cutting torch. In fact, through skillful use of the lance it is possible to aid in the cutting of heavy thicknesses and at the same time to realize a fairly satisfactory type of cut. Somewhat similar to this operation is the use of steel welding rods fed by hand into a deep cut immediately following the usual machine cutting torch. Oxygen lances are successfully used in

opening holes in salamanders, ladle chills, and the frozen metal in the tap holes of blast and open-hearth furnaces.

The lance operation is of great value because it is frequently the only method available for difficult cuts. The surface of a lance cut obviously is not as smooth as cut surfaces obtained by the oxygen cutting torch, but in the hands of an experienced operator remarkably accurate results can be obtained.

The use of the lance is not confined to the cutting of steel. It has been successfully used for the piercing or cutting of non-ferrous metals and even non-metals such as concrete vaults or foundations.

Cast Iron Cutting

Cast iron is difficult to cut, first because of the presence of graphitic carbon which by virtue of its flaky condition offers some protection for the steel against oxidation, and which by virtue of the usual quantity present in cast iron will result in an appreciable CO_2 pollution of the oxygen stream

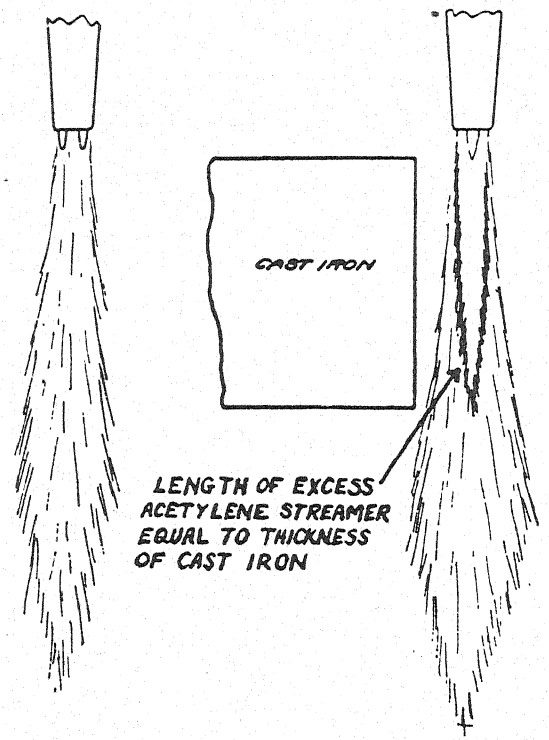


Fig. 22—Flame Adjustment for Cast Iron Cutting

and thereby greatly reduce its reactivity. (See section on "Oxygen Purity".) Moreover, the fact that the melting point of cast iron is less than that of the iron oxides, means that the iron will tend to melt rather than to oxidize. It should be observed that in the more customary oxygen

cutting operations the melting point of the steel is higher than that of the oxide so that the steel beyond the immediate region of oxidation maintains its rigidity, whereas the oxide in a fluid condition is readily washed out of the cut by means of the cutting stream. In this manner a minimum quantity of iron must be removed, and there is a maximum opportunity for a relatively unpolluted oxygen stream to attack fresh regions. With cast iron cutting this fortunate relationship is not involved.

In view of these conditions it should be obvious that to successfully cut cast iron one must think of the operation, to a considerable extent, as a melting operation in which the oxygen jet may be more valuable as a physical eroding and washing agent than as a chemically active agent. Accordingly, it is but logical that in actual practice the preheat for cast iron cutting must be intense. Moreover, it is necessary that much heat be liberated deep in the cut. The former is effected by using larger or more numerous preheat orifices for cast iron cutting than for more normal cutting operations. The latter is effected by adjusting the preheating flames so that combustion is completed in the lower levels of the cut. That is, a considerable excess of acetylene is permitted in the preheating flames, as illustrated by Fig. 22, and this excess of acetylene unites with some of the oxygen of the cutting jet in the lower levels of the cut.

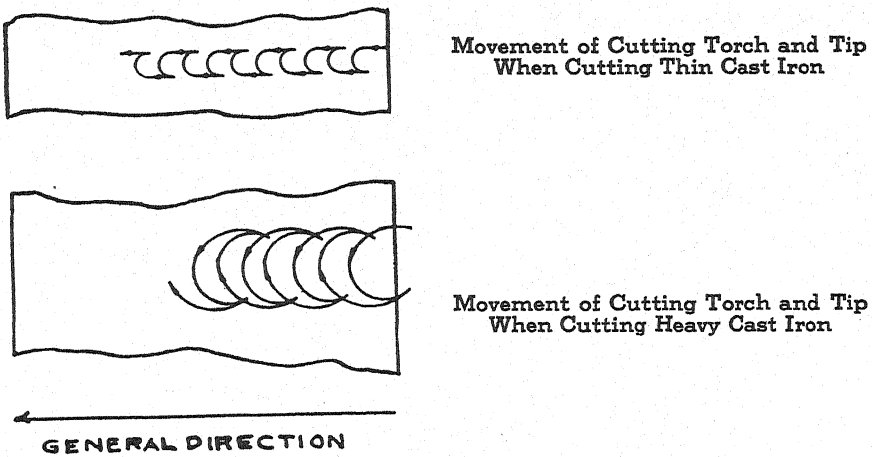


Fig. 23

If the oxygen jet is moved forward continuously as in the ordinary cutting operations, the jet itself will prevent the heat, liberated in the lower regions of the cut as just described, from being effective at the forward or active edge of the cut. Consequently, movements such as those illustrated by Fig. 23 are necessary in order that the intermediate and lower portions of the cut may be maintained at the proper temperature, and in order also that the cut may be wide enough to prevent any possibility of the molten iron freezing in the lower levels.

The details of the cast iron cutting procedure are as follows:

First, the forward edge of the casting is heated along the intended line of the cut by means of a welding torch or the cast iron cutting tip adjusted

for intense preheat. If the piece is very heavy a certain amount of the material may be cut or washed away from the lower portion of the forward face. This will facilitate the starting operation not only by decreasing the thickness that needs to be cut, but also by supplying a considerable amount of heat to the forward portion of the casting. When the forward face has been heated to approximately 200° to 300°F., the cutting torch should be moved to the upper surface of the casting, and held adjacent to the forward edge long enough to melt a small puddle of iron. The torch is then rotated so that the axis of the tip slopes backward at an angle of approximately 45°. The cutting oxygen valve is then opened and the oscillatory motion illustrated by Fig. 23 is started at once. The most desirable radius of the gyration will vary according to the skill of the operator and the size of casting



Fig. 24—Cast Iron Propeller Hub After Being Cut by Oxyacetylene Cutting Torch

being cut. It generally will be on the order of $^3/_{16}$ to $^1/_4$ in. The period of gyration is approximately one or two seconds for each complete movement. At the lateral points where the motion is reversed there should be a pause just long enough for the oxygen stream to effectively wash the molten iron from the bottom of the cut, but not long enough to permit the forward face of the cut to lose its incandescence.

With each individual oscillation the torch must be moved forward just enough to wash a small amount of iron from the active front of the cut, but great care should be exercised not to push the operation too fast.

As the cut gets under way the inclination of the tip should gradually be decreased until the angle with the upper surface of the material is approximately 75° to 80°. The cut may now be completed with this angle of inclination. Because a considerable drag will be involved, it will be necessary for the torch and tip to be slowly carried down the rear face of the material, maintaining the previous inclination in order that the final lower corner may be severed.

The cutting oxygen pressure should not be too high and, in general, it will be found that very satisfactory results are obtained if the oxygen pressure is no more than 40 to 50 lb. for thicknesses up to 6 in., and no more than 75 to 80 lb. for thicknesses up to 15 in. The cutting oxygen orifice should be approximately the same size as recommended for similar thicknesses of steel (see Table 1).

If the operation is skilfully executed with regular movements of the torch, a constant stream of slag and molten metal will issue from the bottom of the kerf and the resulting cut will be quite regular although, of course, considerably rougher than that obtained with oxygen cutting of steel (see Fig. 24).

Cast iron cutting finds one of its most useful applications in the preparation of castings for welding or brazing. The cast iron cutting method is efficient and practicable for veeing the edges of broken parts which are to be repaired in this manner. It is also useful as a demolition tool, particularly where heavy machinery is so situated that it is impracticable to break it into smaller fragments by more usual methods.

Flame Machining

Oxyacetylene cutting processes may be classified under two subdivisions, usual oxygen cutting and flame machining. The former includes most severing operations, while the latter consists of various surface shaping operations. At the present time usual oxygen cutting is more extensively

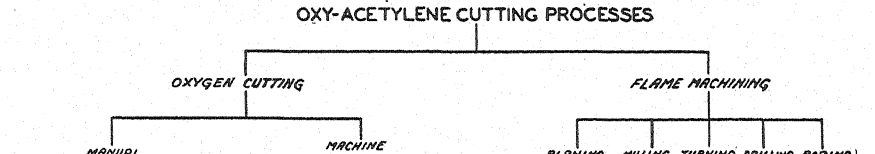


Fig. 25—Classification for Oxyacetylene Cutting Processes

developed, but flame machining promises also to become very important and valuable as a formative process for the preparation and shaping of steels. (For recent developments in flame machining and plate edge preparation see references 33 and 34.)

Flame machining consists in removing material by surface oxidation. The operation is analogous to tool machining, but the tool in this instance is an oxygen jet. Sub-classifications of flame machining include many of the same operations as tool machining; prominent among these are planing, milling, turning and drilling (see Fig. 25).

Not all the operations listed in Fig. 25 under the heading "Flame Machining" have been commercialized up to the present time as some are still in the development stage. A general idea of the progress of the art may be gained from Fig. 26, which shows a typical flame machine part.

Each operation in flame machining constitutes a problem unto itself. Complete coordination between nozzle design and metallurgical control is required to produce results satisfactory for final tool finishing of the part in question. In all cases machine-guided flame machining leaves a bright and uniform smooth finish that is highly satisfactory for subsequent welding or machining work.

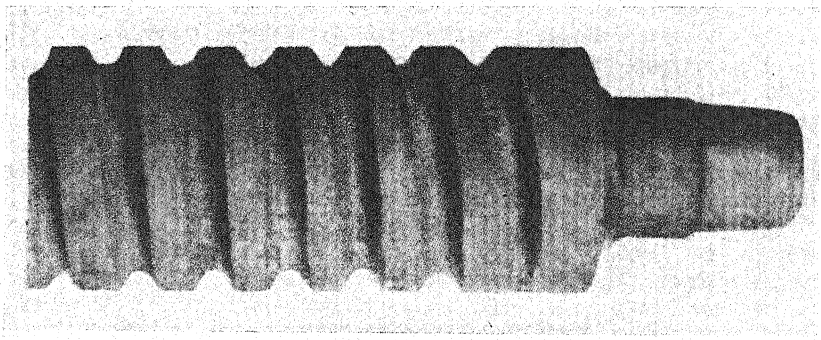


Fig. 26—Coarse Pitch Screw Flame Machined

Under the heading of "Flame Planing" (Fig. 25) there are several kinds of cuts, differing chiefly in the nature of the application and the cut profile. The profile of a cut and the general surface conditions resulting can be varied considerably.

One of the most important commercial applications of flame planing is "deseaming" or "gouging." This process is extensively used for removing cracks or surface seams or oxide and scale from billets, slabs and rounds enroute to the various finishing departments of steel mills. Foundries also employ it for cleaning out cracks and sand holes in steel castings. Typical cross-sections and dimensional ranges of deseaming cuts are shown in Fig. 27.

"Hogging" is an increasingly important foundry process which is used for removing superfluous metal from steel castings. It includes the removal of risers and sprues which are often of such a nature or so located that it is difficult or impossible to remove them by ordinary oxygen cutting methods. Hogging cuts are very similar in cross-section to those illustrated in Fig. 27. The depth of the cut, however, may be considerably greater when required. Such deep cuts are sometimes characterized by rough surfaces, but subsequent flame planing will provide a satisfactory finish. Gang as-

sembly of planing tips or nozzles have been used for certain types of hogging cuts.

These cuts, however, are more typical of what has been termed "surface planing." In this operation cuts are made in parallel relationship, permitting the removal of wide surfaces (see Fig. 27, *c* to *g*). When performed mechanically, close dimensional allowances on depth and width of the individual cuts may be maintained so that the resulting finished surfaces are at least equal to those formed by rough surface tool planing. Control of surface regularity is dependent on the selection of the proper profile style and on the careful spacing of the cutting tips.

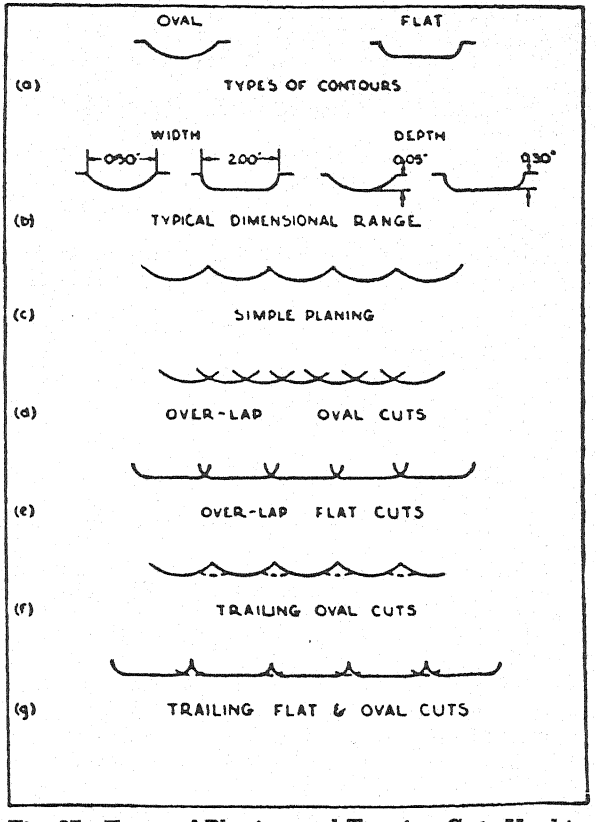


Fig. 27—Types of Planing and Turning Cuts Used in Flame Machining

Turning operations are, of course, similar to the planing operations just described, although this particular phase of the process is so recent that few commercial applications have as yet been made.

Flame machining must inevitably increase in importance because it constitutes a rapid and, generally speaking, a relatively inexpensive method of removing excess material. Even with equipment now available metal may

be removed at a rate of 10 to 15 lb. per min. The oxygen consumption with present practice amounts to approximately 3 cu. ft. per lb. of steel removed. The power requirements for moving the torch or steel or turning the latter are almost negligible. Moreover, very light weight, inexpensive equipment is adequate to accomplish rapid heavy roughing operations that otherwise would require massive and powerful machinery.

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CHAPTER 16B

FLAME GOUGING*

Oxyacetylene Gouging—a Flame-Machining Process, Gouging the Underside of Groove Welds, Removing Weld Defects, Plate-Edge Preparation, Maintenance and Scrapping Applications, Gouging Apparatus, Gouging Technique, Contour of the Groove, Spot-Gouging Technique.

Oxyacetylene Gouging—A Flame-Machining Process

OXYACETYLENE gouging is a rapid and economical method of forming U-shaped grooves by removing surface or edge metal from rolled, drawn, forged or cast steel. In general gouging applications can be classified into the four following groups:

1. Progressive gouging of the underside of electric arc welds.
2. Spot gouging in the removal of defective weld metal and temporary tack welds.
3. Plate-edge preparation for welding.
4. Maintenance and scrapping operations.

The success of the gouging process depends upon the design of a special nozzle to deliver a relatively large volume of oxygen at low jet velocity. This jet, coupled with proper preheat flame distribution and guided by a simple gouging manipulation, will cut a smooth, accurately defined groove in the surface of steel plate. By using different nozzles and manipulations the groove can be varied in width and depth at the will of the operator.

The process is somewhat similar to that of hand-deseaming or "scarfing", the principal difference being that the degree of accuracy of metal removal with a gouging blowpipe is considerably greater than that with a deseaming blowpipe. In conditioning steel billets and slabs by deseaming the primary object is to remove a wide, shallow layer of metal thus eliminating surface defects and leaving the resulting surface prepared for subsequent rolling operations. Gouging, with its characteristic U-shaped groove contour, removes the surface or edge metal in such a way as to prepare a groove properly shaped for welding operations.

* Prepared by a committee consisting of H. E. Rockefeller, The Linde Air Products Co., *Chairman;* E. C. Chapman, Combustion Engineering Co., Inc.; G. V. Slottman, Air Reduction Sales Co.

Gouging the Underside of V or Groove Welds

One of the original and major applications for gouging has been in the removal of the underside of welds. For fabrication of tanks and vessels of butt-welded construction where double-welded joints are called for, it is generally specified that the root of the initial weld be removed before the back weld is made. Gouging has provided a means for accomplishing this operation not only much faster but also considerably more economically than other methods of weld-metal removal.

Figure 1 illustrates the application of gouging to double-welded joints with U-groove preparation, double-vee preparation and single-vee preparation with backing-up strip.

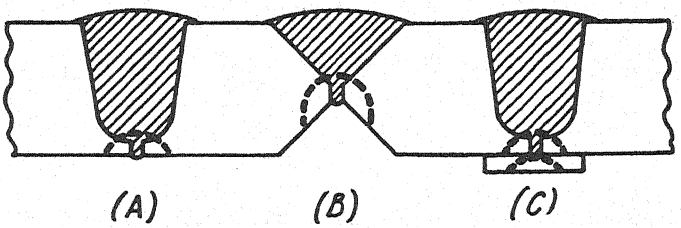


Fig. 1—Conventional Weld Designs, with Dotted Lines to Indicate the Metal Removed by Gouging. *A*, U-groove; *B*, Double Vee; *C*, Single-Vee Preparation with Backing-Up Strip

Removing Weld Defects

The removal of weld metal such as weld defects, temporary welds and tack welds is classified under the title of "spot gouging." In this type of work the need for positive control of the cutting action is of major importance. The gouging operator can quickly and accurately remove the spots or areas of metal which X-ray, gamma-ray or visual inspection designates for removal.

In the modern fabricating shop doing the class of work upon which X-ray or gamma-ray inspections are standard practice for checking weld quality, the gouging blowpipe proves to be a valuable tool. Figure 2 shows a typical weld in which patches of porosity or inclusions are indicated. The dotted lines enclose the area of metal which is removed by the gouging process. The cutting action is controlled to cut just deep enough to remove the unsound metal. In this operation the blowpipe is not moved forward as in progressive gouging but is manipulated to remove the least amount of weld metal necessary to simultaneously eliminate the weld defect and prepare a gouge suitable for welding. The resulting narrow gouge slopes sharply downward from the surface of the plate from each end, resulting in conditions of highest economy for repairing the weld.

Plate-Edge Preparation

A gouging application which is gaining in importance is the preparation of plate edges for welding. Three types of edge preparation are employed.

First is the full U-grooving of abutting plate edges. Second is the J-grooving of the edge of a single plate. Third is the U- or J-grooving of heavy plate, above $1^1/_2$ in. in thickness, by a combination of beveling and gouging.

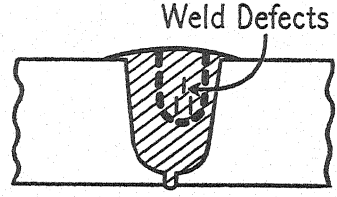


Fig. 2—Weld Defects Which Can Be Removed by Gouging

Figure 3 illustrates a speedy and economical method for preparing simultaneously two butted plates for welding. The plates are butted or spaced apart as shown and a single bead welded down the seam. The dotted portion is then removed by gouging to form a clean U-groove for welding with a backing-up bead in place. The initial bead may or may not be removed later. An excellent job can be made by hand in preparing joints of this type in plate up to $^3/_4$ in. thick.

Joint design specifications often require a U- or J-edge preparation for welding on plate in the heavier thicknesses in preference to the vee edge preparation. In order to provide clearance for the electrode at the bottom of the vee, an angle would have to be selected which would require an excess of weld metal. In order to gain the economies of the oxyacetylene process for preparation of plate edges on heavy plate thicknesses, a combination bevel and gouge technique has been developed.

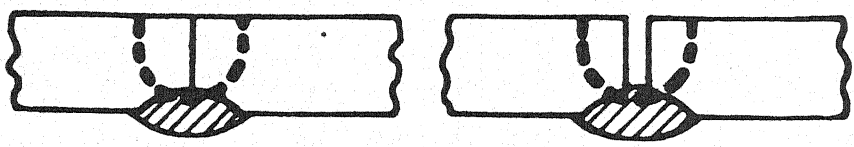


Fig. 3—Complete U-Groove Preparation of Abutting Plate Edges

This process is entirely mechanized and the quality of the flame-machined surfaces is exceptionally high. Figure 4 shows the mechanical set-up in action while making the second or gouging pass. A fabricator of diesel locomotive frames has used this method for the preparation of plates 40 ft. in length.

Maintenance and Scrapping Applications

Another application of importance in which the gouging process has found immediate acceptance is in the field of maintenance and repair operations. The importance of rapidly repairing and restoring to operation a piece of

machinery which has broken down is a major factor in maintenance work. The welding processes were a particular boon for this type of work. Now, gouging complements the welding process to reduce the repair time still further.

Figure 5 illustrates an interesting oil refinery problem. Gouging is being widely used in removal of still tubes. Previous practice called for oxy-

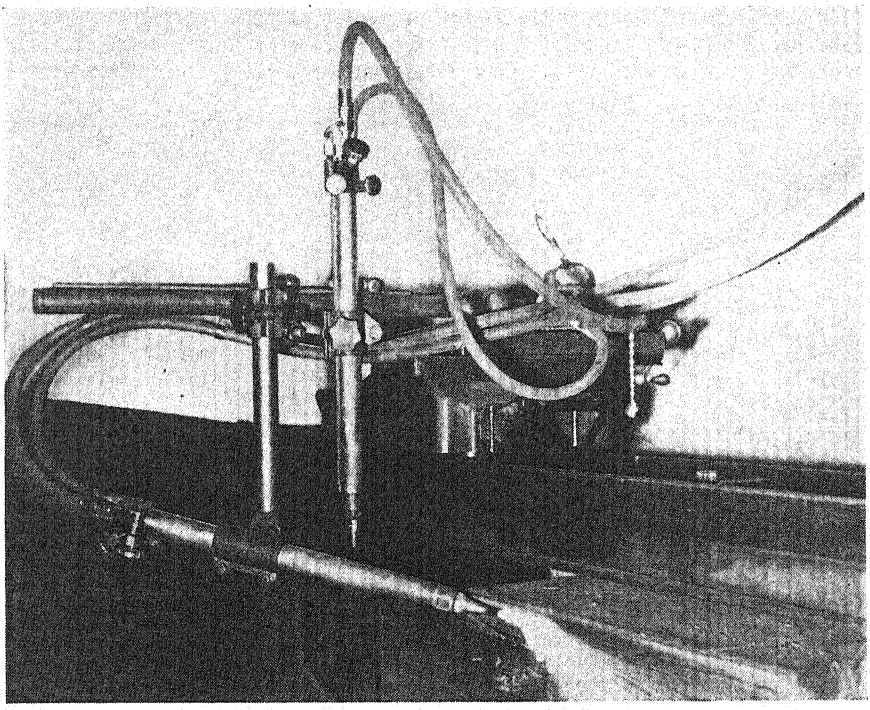


Fig. 4—Heavy Plate Being Prepared for Welding by Gouging. Plate Shown Has Already Been Beveled. The Gouging Blowpipe Set-up, in a Planer, Is Being Used to Make the Second Pass to Provide the Desired Edge Contour

acetylene cutting of the tube close to the header casting and then grooving the stub with a hammer and cold chisel so that it could be collapsed. This procedure was followed in order to minimize the chance of damage to the header casting. Gouging has largely taken the place of chipping for the grooving of the stub. The operation can be readily controlled so it will carry only deep enough to permit collapsing the tube without injury to the header.

A similar application in another field is the use of gouging for such operations as removal of pipe stubs or "Dutchmen" from salvaged valves, collars, tees and other fittings.

An interesting flame-machining application is illustrated by the shaping of the end of an 8-in. shaft so that it would fit into a rolling-mill drive

clutch or "wobbler." Each splineway shown in Fig. 6, about 3 in. wide and 12 in. long, required only about 30 min. to groove and only a light grinding was necessary to finish the shaft for service.

Gouging Apparatus

Standard hand-cutting blowpipe and gouging nozzles, besides fitting standard blowpipes with 75° and 90° heads, also can be used with a special 180°, straight blowpipe. It has been observed that new operators unfamiliar with all phases of oxyacetylene cutting can grasp the gouging technique more readily if trained to use the straight blowpipe. Experienced cutting operators usually prefer the 75° or 90° blowpipe. They have found that they can operate these blowpipes skilfully with only a slight modification of the hand-cutting technique.

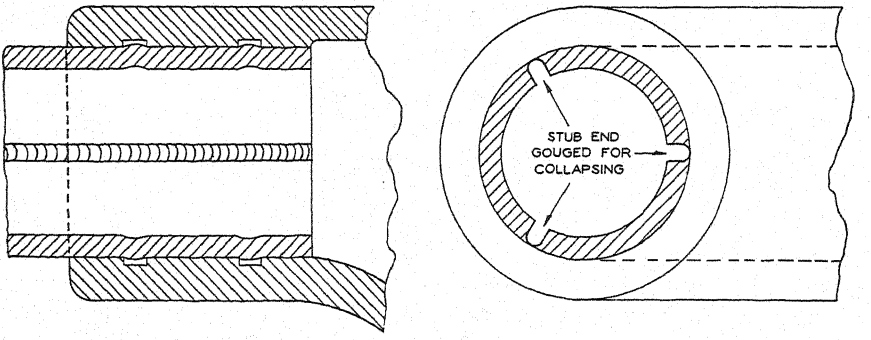


Fig. 5—Method of Removing Boiler Tubes from Oil Refinery Headers

Gouging Technique

There are, in general, two different techniques for gouging: one in which a groove is made progressively across a plate, as in the removal of metal from the underside of welds; the other, known as spot gouging, in which a small area is gouged out, as in the removal of isolated weld defects. In the first, or progressive method, the correct nozzle is selected and oxygen and acetylene pressure regulated to give the desired width and depth of groove as indicated in Table 1.

In starting the cut the blowpipe is held with the end of the nozzle at an angle of approximately 20° to the horizontal and above the line of cut, as shown in Fig. 7. The preheat flames are played on the spot where the cut is to be started until the surface reaches the ignition point. The cutting-oxygen lever is then gradually depressed. The cut progresses slowly while the angle of the end of the gouging nozzle is gradually reduced to the correct operating position. This angle, as illustrated in Fig. 8, will be readily discernible by the operator. If the nozzle is not lowered far enough, some of the slag will tend to flow backward in the cut toward the operator; if the blowpipe is lowered too far, the groove will become shallow and will soon be lost. Figure 9 shows a close-up view of the operation in progress. Two feet per minute is the approximate speed of travel of the gouging blowpipe in making this clean groove, $^3/_8$ in. wide and $^1/_4$ in. deep, in steel plate.

Table 1—Operating Data for Gouging Nozzles

Nozzle Drill Size, In.	Regulator Pressure,* Lb. per Sq. In. Acetylene	Oxygen	Consumptions, Cu. Ft. per Hr. Acetylene	Preheat Oxygen	Cutting Oxygen	Approximate Speed, Ft. per Min.	Approx. Gouge Dimensions, In. Width	Depth
.013	10	65	35–38	35–38	78–82	1.0–1.2	5/16	1/8–3/16
.013	10	70	35–38	35–38	88–92	1.4–1.6	5/16	5/32–7/32
.013	10	75	35–38	35–38	98–102	1.5–1.8	5/16	3/16–1/4
.019	10	80	50–55	50–55	170–175	1.6–1.9	3/8	3/16–1/4
.019	10	85	50–55	50–55	188–192	1.8–2.0	7/16	7/32–9/32
.019	10	90	50–55	50–55	205–210	1.9–2.2	7/16	1/4–3/8
.025	10	90	55–60	55–60	278–282	1.9–2.2	1/2	3/16–1/4
.025	10	95	55–60	55–60	308–312	2.3–2.6	1/2	1/4–3/8
.025	10	100	55–60	55–60	328–332	2.5–2.8	1/2	5/16–7/16

* Pressures measured at the regulator. Nozzles can also operate on low-pressure acetylene.

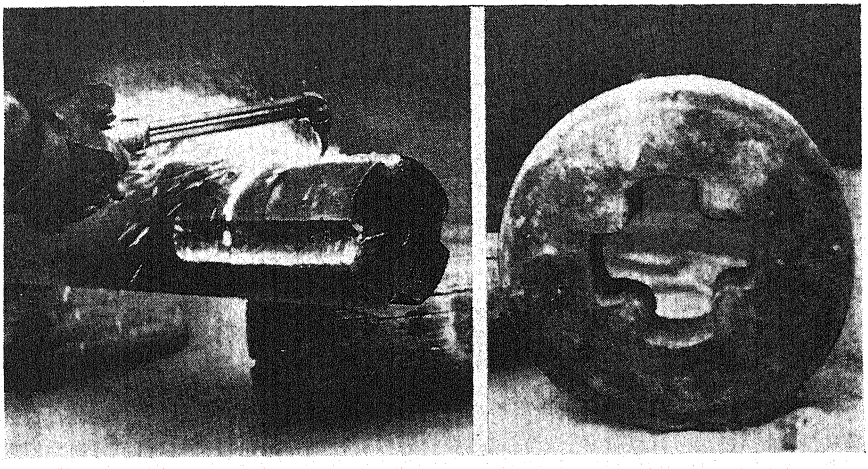
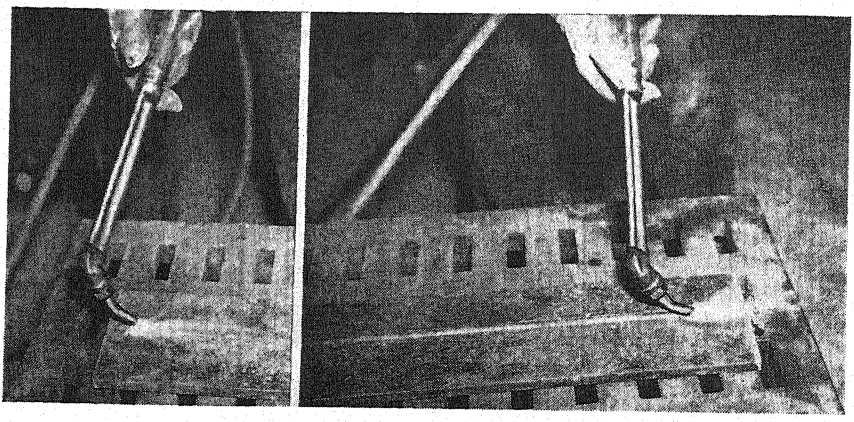


Fig. 6—The Shaping of the End of an 8-In. Shaft So That It Will Fit Into a Rolling-Mill Drive Clutch

In starting the gouge, the blowpipe is held so that the tips of the inner cones of the preheat flames are just touching the work. After the cut is started, however, the nozzle is held above the surface of the cut with the tips of the inner cones from 1/4 in. to 1/2 in. back of the reaction zone. Best results are obtained when the blowpipe is held so that the nozzle clears the bottom of the groove.

When it is necessary to change the direction of the cut, the angle of the nozzle in relation to the work should remain unchanged while the blowpipe is rotated in the new direction. Too sharp a turn should be avoided lest the outside wall be cut into as the result of the action of the molten slag. It is advisable to use lower cutting-oxygen pressures than those indicated in Table 1 when not cutting in a straight line.



Figs. 7 and 8—The Angle of Nozzle for the Correct Impingement for Starting and for Carrying the Gouging Cut

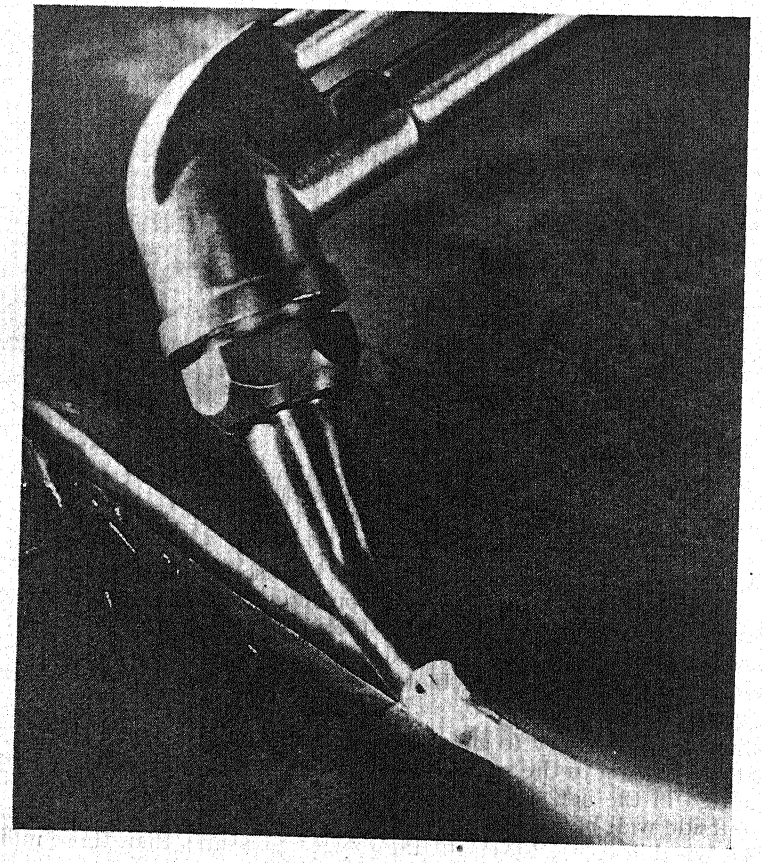


Fig. 9—A Close-Up of the Metal Removal Operation

Contour of the Groove

The depth of the groove is a function of the speed of progression and the angle between the cutting-oxygen stream and the work. To cut a deep groove the angle of the blowpipe is increased in relation to the groove and the speed is correspondingly decreased. In order to make a shallow groove the procedure is reversed. With the establishment of the correct depth of cut, it is an easy matter to maintain this depth throughout the full length of the cut. Grooves can be made that are as deep as or slightly deeper than they are wide.

The contour of the groove is dependent upon the characteristics of the nozzle used and the operating conditions. If the cutting-oxygen pressures are too low, the cutting takes on a washing effect, leaving ripples in the bottom of the groove. The effect of too high cutting-oxygen pressures is to advance the portion of the cut nearest the surface ahead of the rest of the molten zone with the result that the cut is finally lost.

Spot-Gouging Technique

In gouging out a spot, such as a single weld defect, the defect is first marked out on the surface of the weld. A starting point is next selected a little to the rear of the mark, depending on how deep the defect is judged to be. The cut is then started in the usual manner by preheating the spot but instead of reducing the angle of the nozzle, it is increased gradually so that the oxygen jet is directed downward, making the cut increasingly deep. As in deseaming, a little experience enables the operator to observe readily any defects which appear as dark spots in the molten zone.

The blowpipe should be held so that the inner-cone tips of the flames are about $^1/_{16}$ in. above the plate surface at all times during the cut. The resulting cut is a narrow U-shaped groove which can readily be filled with weld metal.

Specifications S-1, S-2 and S-55 of the 1940 A.S.M.E. Boiler Construction Code cover carbon steel plates used for boilers and unfired pressure vessels. Both A.S.T.M. and A.P.I. also provide for these materials. The maximum carbon content is 0.35 per cent. Such steels can be successfully processed with the gouging blowpipe.

As a general rule, gouging should not be applied to air-hardening steels where the hardness will be objectionable. For example, clips should not be removed from the surface of a vessel where the carbon content of the plate is so high as to cause the formation of a hardened zone having decreased ductility.

Care should be used in gouging alloy steels. Test cuts should first be made in scrap pieces and the operator should determine from these cuts whether the characteristics of the metal about the cut have been altered too drastically.

CHAPTER 16C

ARC CUTTING*

Carbon Arc Cutting, Coated Electrode Cutting, Miscellaneous Applications.

Introduction

THE process of arc cutting is purely a method of applying the heat energy of the electric arc to melt the metal along a desired line of cut. It does not compare with gas cutting from the standpoint of smoothness and quality of the cut surfaces, but with reasonable skill and experience a very neat cut can be made on steel plates, as shown in Fig. 1. The relative costs of arc and gas cutting depend upon the material being cut. Gas cutting is less expensive for mild steels, while arc cutting is less expensive on certain specific materials, such as cast iron and non-ferrous metals.

Arc cutting is generally confined to scrap, cast iron, non-ferrous metals, stainless steels, hole piercing, rivet cutting, nick-breaking and other special uses where its particular characteristics can be used to advantage. Its primary advantage over gas cutting lies in the fact that it is applicable to all types of metals.

Carbon Arc Cutting

The process of carbon arc cutting consists essentially of drawing an arc between a carbon or graphite electrode and the material to be cut, and allowing the heat of the arc to melt away the material. Direct current

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* Prepared by a committee consisting of C. H. Jennings, Westinghouse Electric and Manufacturing Co., *Chairman*, and C. J. Holslag, Electric Arc Co.



Fig. 1—Typical Cut Made with Carbon Arc

energy is generally used with the carbon electrode negative (straight polarity), although alternating current energy can also be used.

Soft carbon electrodes are sometimes used for arc cutting, but they are not generally recommended because of their short service life resulting from the heavy current values required in arc cutting. Graphite or hard carbon electrodes have a service life many times that of soft carbon electrodes and have consequently found general acceptance for this class of work. Graphite and hard carbon electrodes will also retain a point longer than soft carbon electrodes and this is an essential factor where clean, smooth cuts are required.

The heavy currents required in arc cutting render electrode holders of the type ordinarily used for arc welding unsuitable except when small diameter electrodes are used. For small electrodes, an adaptor (Fig. 6) has been found satisfactory. For large diameter electrodes, special holders are desirable. These holders contain a long shank, a hand shield to protect the operator's hands from the intense heat and a special gripping mechanism for holding the electrode.

The manipulation of the cutting arc is simple. When cutting thin plates ($^3/_8$ in. or less) the arc is simply advanced along the section to be cut at a rate equal to that at which the metal is melted away. The cutting operation may be done with the plate in the horizontal, inclined or vertical positions. The most smooth and uniform cuts are obtained with the plate in the horizontal plane.

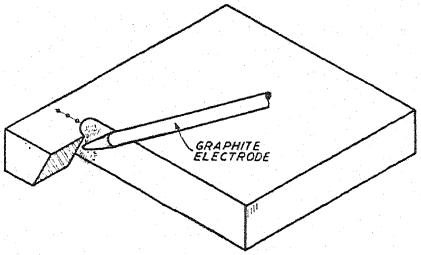


FIG. 2 - METHOD OF CUTTING THICK PLATES. THE BOTTOM OF THE CUT IS ADVANCED SLIGHTLY AHEAD OF THE TOP OF THE CUT.

The angle at which the electrode is held depends upon the plane of the plate being cut. In horizontal cutting, the electrode may be held either vertical or pointing slightly forward. When cutting plates in the inclined or vertical planes, the electrode should be pointed downward.

When cutting materials heavier than $^3/_8$ in., the process consists of progressively melting away the vertical face of the cut. The procedure generally employed in this case is to work from the top to the bottom of the plate, thereby having the bottom of the cut advanced slightly ahead of the top of the cut (see Fig. 2). This method of procedure produces an undercut which permits the molten metal to run out more easily.

The speed of cutting increases with increased current. The width of the cut increases with increased current values and electrode diameters.

The skill of the operator also has a large influence on the width of the cut.

Recommended current values for different sizes of graphite electrodes are given in Table 1.

Table 1—Current Values for Various Sizes of Graphite Electrodes

Electrode Diameter, In.	Current Values, Amp.
1/4	Up to 200
3/8	200– 400
1/2	300– 600
5/8	400– 700
3/4	600– 800
7/8	700–1000
1	800–1200

The fact that cutting depends entirely upon melting away the material by the heat of the arc, rather than the process of oxidation as in the case of gas cutting, makes it possible to cut rolled steel, cast iron and most alloys and non-ferrous materials at the same rate. Typical cutting speeds for plate materials are given in Fig. 3. Cutting speeds for circular bars are given in Fig. 4.

Coated Electrode Cutting

The major portion of all arc cutting is done with graphite or carbon

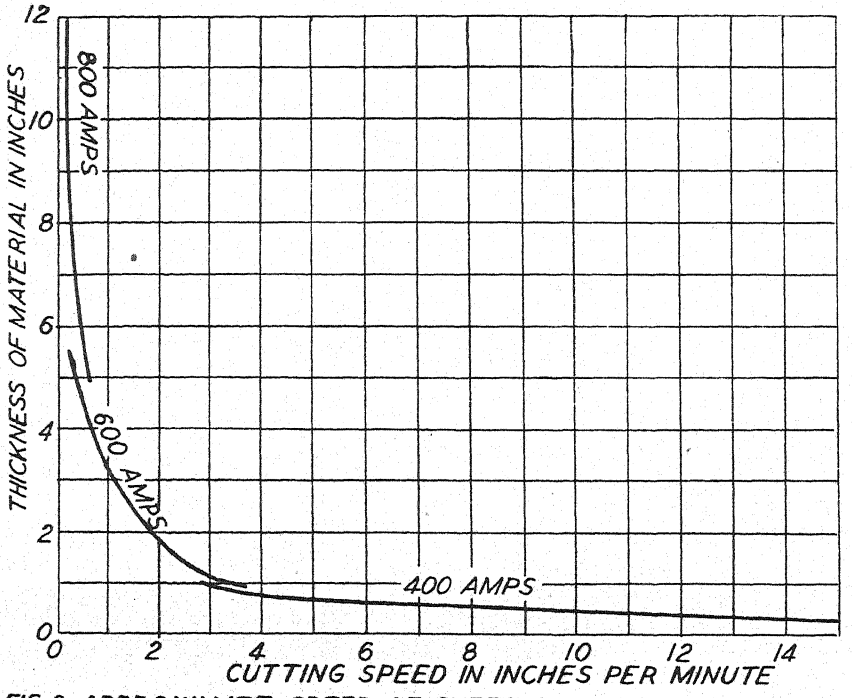


FIG. 3-APPROXIMATE SPEED OF CUTTING STEEL AND CAST IRON PLATES

electrodes, but it is desirable to point out the application of coated electrodes for this process. The application of coated electrodes to cutting is not always an economical process because of the cost of the electrodes, but it has certain merits. It has been found particularly advantageous in cases where a small job of cutting is required and an oxyacetylene torch or carbon electrode is not available for this purpose.

Electrodes with both gaseous and slagging type coatings can be used for arc cutting, but in general the latter type gives the better results because

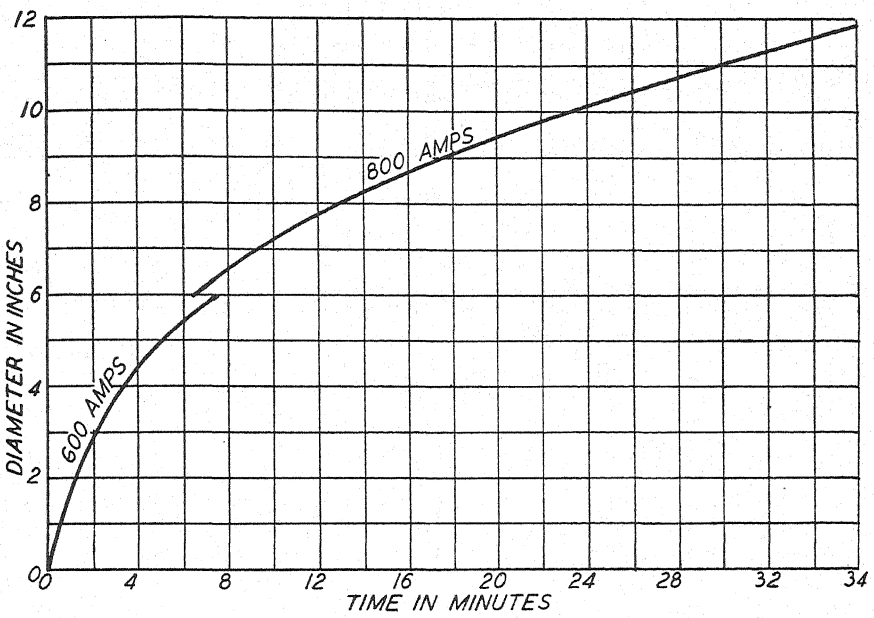


FIG.4 :- APPROXIMATE SPEED OF CUTTING CIRCULAR STEEL AND CAST IRON BARS

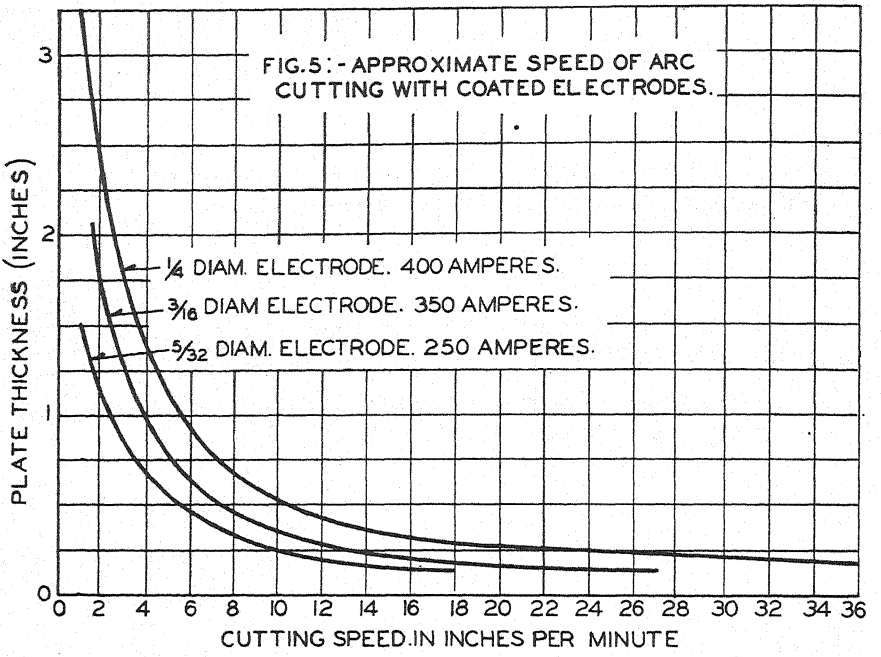
they will handle higher current densities. Either direct or alternating current can be used when cutting with coated electrodes.

The speed of arc cutting with coated electrodes depends upon the electrode diameter and the cutting current. Electrodes smaller than $^5/_{32}$ in. in diameter are not suitable for arc cutting because they heat up quickly and melt away under the high currents employed.

Plate up to $^1/_4$ in. thick can be cut by simply moving the electrode along the line of cut. On heavier plates it is desirable to point the electrode forward and move the electrode from the top to the bottom of the cut so as to have the bottom of the cut slightly advanced. (Similar to the carbon arc cutting process illustrated in Fig. 2.)

Cutting speeds obtained on steel and cast-iron plates with different diameters of electrodes (slag-coated type) are shown in Fig. 5.

Alloy steels and non-ferrous metals can also be readily cut by the coated



electrode cutting process. In these cases it is often not necessary to use an electrode of the same composition as the base metal. By using the proper type of electrode, however, cuts can be made on special alloy steels without adversely affecting the metallurgical characteristics.

Miscellaneous Applications

In addition to straight or seam cutting, the electric arc is applicable to many special types of cutting jobs.

Rivet Cutting.—The arc-cutting process is used extensively for cutting rivets. It has been found to be one of the quickest methods of removing rivet heads, and it does not involve the disadvantages of some of the other processes. It eliminates the danger of the mechanical rivet busters and does not produce undercutting of the plates.

When cutting rivets, the best results are obtained with the plates in the vertical position. If the plates are in the horizontal position, rivet heads may be successfully cut from either the top or bottom sides of the plates. When cutting rivets from the top of the plate, it is necessary to remove the molten metal by an air blast or by mechanical means. If the rivet head is cut from the bottom of the plate, the force of gravity will remove the molten metal as is the case when removing rivets from vertical plates.

If it is desired to salvage the riveted plates, the arc should not be struck on the plates as this is likely to burn a depression in them. The arc should

be struck on the rivet head and a slight rotary motion applied, care being taken not to concentrate the arc too long at the periphery of the rivet head.

The removal of rivets by the arc process has been used extensively by railways in rebuilding freight cars because of its economic advantages. Average operators can cut 1800 to 2000 rivets a day while in some cases this number can be increased 50%.

For the best results in rivet cutting, $^1/_2$- to $^5/_8$-in. graphite electrodes should be used with 400 to 600 amperes of current.

Hole Piercing.—In addition to seam cutting, coated electrodes can also be used to pierce holes in plates. Hole piercing has many applications in cases where a hole is desired and it is impractical to punch or drill it. This process is easy and quick.

The application of coated electrodes to hole piercing is dependent upon the formation of a crater at the end of the electrode which is the result of the steel core melting away in advance of the surrounding coating. After the crater has been formed it is possible to push the electrode against the plate without shorting the circuit. Upon pushing the electrode against the plate, the protruding coating and not the metal core touches the plate. Consequently, there is still a gap between the metal conductors and the electric arc does not become extinguished by the action.

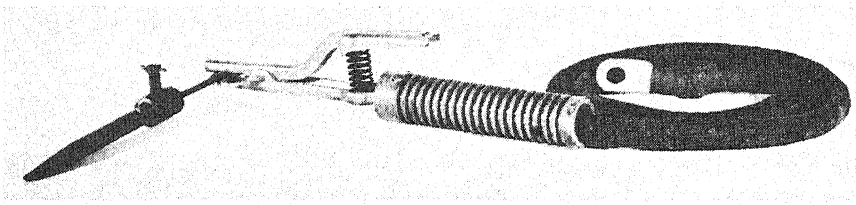


Fig. 6—Adaptor for Holding Carbon Electrode

Hole piercing is done by applying high currents to the electrodes. The arc is drawn at the point where the hole is to be pierced and the electrode moved in a circular motion equal to the diameter of the hole to be pierced until the surface is melted. Following this, the electrode is pushed down against the molten metal and the circular motion continued. The continued application of pressure while rotating the electrode will cause the electrode to melt a hole through the plate. If the process is properly carried out, clean, circular holes can be produced, and little difficulty will be experienced.

If it is desired to pierce a larger diameter hole than can be made by the above process, a two-step operation should be used. First a central hole should be pierced as previously described. Following this, a long arc can be drawn between an electrode and the inner periphery of the hole. By moving the arc around the hole periphery the base metal will be melted away. Holes of extremely large diameter can be pierced by this method.

If the hole is being pierced in a thick plate, an up and down motion similar to that shown in Fig. 2 should be used when melting away the hole periphery.

Deseaming.—The electric arc has proved satisfactory for many deseaming operations. Typical applications are: removing flaws in castings preparatory to repairing by welding, removing cracked or unsatisfactory welds, beveling joints on materials where the oxyacetylene process is not applicable, removing the back of joints to facilitate the deposition of a seal bead, and removing flaws in rolled plates.

When using the electric arc for deseaming purposes, it is desirable that the member on which deseaming is being done be approximately in the vertical position. Both carbon and metallic electrodes can be used.

It is important to point out that the electric arc does not produce as clean a deseaming job as the gas torch. Also, on certain materials the intense heat applied might have an undesirable effect on the base material. When properly applied, however, electric arc deseaming will be found convenient and entirely satisfactory.

Nick-Breaking.—In industrial applications where it is desirable to cut medium or high carbon bars (above 0.30% carbon) into short lengths, the electric arc has proved highly successful. The electric arc is used to nick the bars at the location where fracture is desired and the bars are ultimately fractured by sharp blows delivered by a bulldozer or some other suitable means.

Drawing the electric arc across a steel bar containing more than 0.30% carbon has two effects: first, the arc heat melts a small groove in the bar and, second, rapid cooling from the molten temperature produces an extremely hard and brittle area adjacent to the groove. When an impact force is applied to this zone the brittle area readily fractures. If the force of the blow is great enough, this initial brittle fracture will progress across the entire bar. If the initial blow only starts the fracture, subsequent blows will cause it to progress across the bar.

During the first World War this process was used to nick-break shell stock. The blanks thus formed were within the correct size and required no additional cutting.

CHAPTER 16D

UNDERWATER CUTTING AND WELDING*

Underwater Cutting, Gas Cutting, Arc Cutting, Underwater Arc Welding.

Underwater Cutting

UNDERWATER cutting has been accomplished by various means since as early as 1908; however, its use has not been extensive due to the inherent handicaps that are presented by underwater work. In most cases its use has been the result of a necessity for work to be done that could not be done by any other means.

The apparatus used has been of considerable variety but it may be grouped in two general classes (*a*) gas and (*b*) arc, based upon the method used to obtain the necessary preheat to perform the cutting operation.

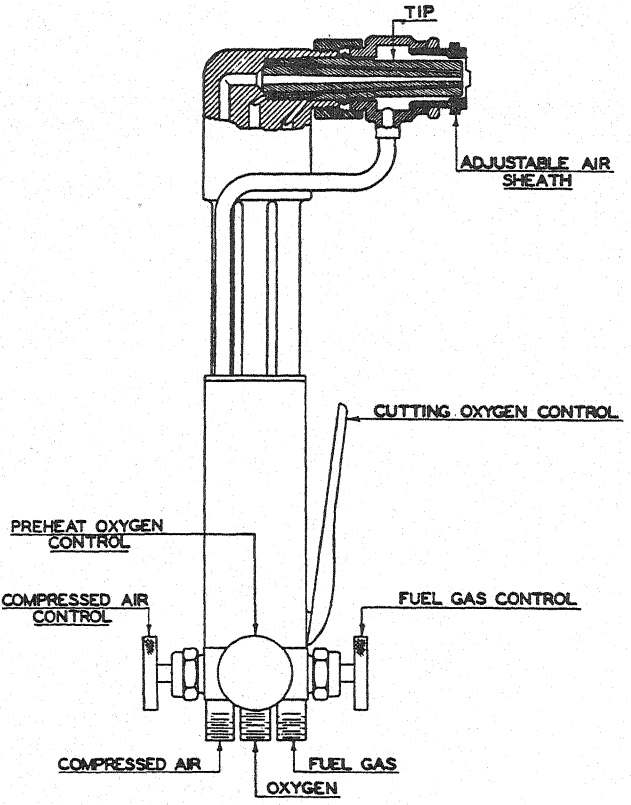
Gas Cutting

Gas underwater cutting torches utilize acetylene or hydrogen as the fuel gas. The higher flame temperature of acetylene makes this gas the more desirable, but it is dangerous to feed it to ordinary torches at depths greater than about 25 ft., so hydrogen is commonly used for work in deeper water. Improvements in torches utilizing the low-pressure injector principle enable the use of acetylene at much greater depths without excessive pressure on the fuel gas, and this practice is becoming increasingly popular.

The torches used in underwater cutting are basically the same in construction as standard gas-cutting torches. The tip is equipped, however, with a means of surrounding the flame with an envelope of air, and a valve to regulate this air supply is added to the usual controls of the torch. It is generally desirable to provide guides to help the diver hold the torch at the correct distance from the work as in most cases the visibility is very poor. A typical example of such a torch is illustrated by Fig. 1. Since the fuel gas and oxygen contain all of the elements necessary for combustion, it is possible to immerse the conventional gas torch in water without extinguishing the flame. For practical work, however, it is necessary to surround the flame with air to stabilize the flame and hold the water from the

* Prepared by a committee consisting of A. G. Bissell, Bureau of Ships, *Chairman;* Lt. John L. DeTar, U. S. N., U. S. Navy Deep Sea Diving School; Lorn Campbell, Jr., Harris Calorific Co.; E. L. Mathy, Victor Equipment Co. The material presented represents the personal opinions of the authors and does not necessarily represent the opinions of their respective organizations.

spot being heated. The distribution of air around the flame should be as uniform as possible, and should be supplied through a narrow passage completely surrounding the tip to prevent the flame or work being partially flooded. Clearance between the sheath or jacket and the work by means of the guides is necessary to permit escape of air and products of combustion. The torch is usually lighted in air and then lowered in the water, increasing the gas pressure as descent is made, or it may be lighted by the diver from an electric spark igniter.

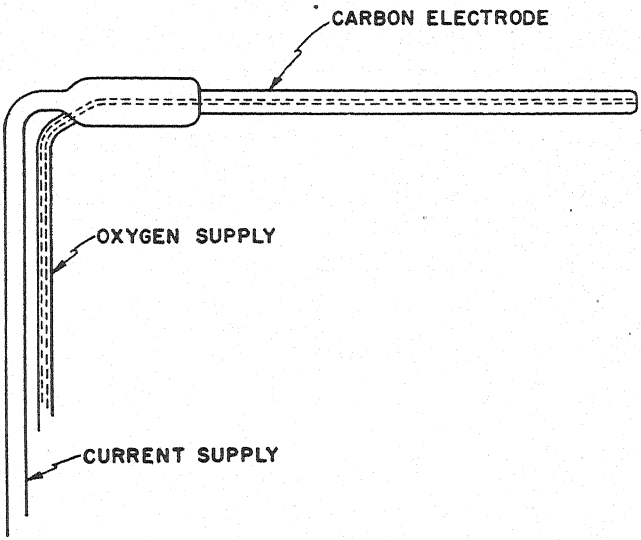


GENERAL SCHEME OF UNDERWATER GAS CUTTING TORCH

Fig. 1

The use of the gas torch for underwater work is practically limited to the cutting of steel. Practical results are not obtained in cutting cast iron, stainless steels or non-ferrous metals. Thin steel also presents considerable difficulty to the gas underwater cutting torch, presumably because of the lack of metal mass to maintain the necessary preheat to support combustion. For the heavier weights of steel plate, the oxy-hydrogen cutting torch is believed to be the most efficient method of cutting under water.

Because of the increased flame intensity required, it is necessary to use higher pressures than are used for corresponding work in air. To these pressures must be added a sufficient amount to overcome the hydrostatic pressure at the depth where the torch is being operated. The exact pressures required will depend upon the type of torch and tip and character of work being done. Because of widely differing conditions under which the work may be done, and the many handicaps under which the operator must labor, it is extremely difficult to estimate the amount of gases required. On straight cutting of medium plate at moderate depths, the consumption may be figured at approximately four times that required for corresponding work in air, but difficult work at greater depths may require greatly increased amounts of gas.



GENERAL SCHEME OF UNDERWATER ELECTRIC CUTTING TORCH

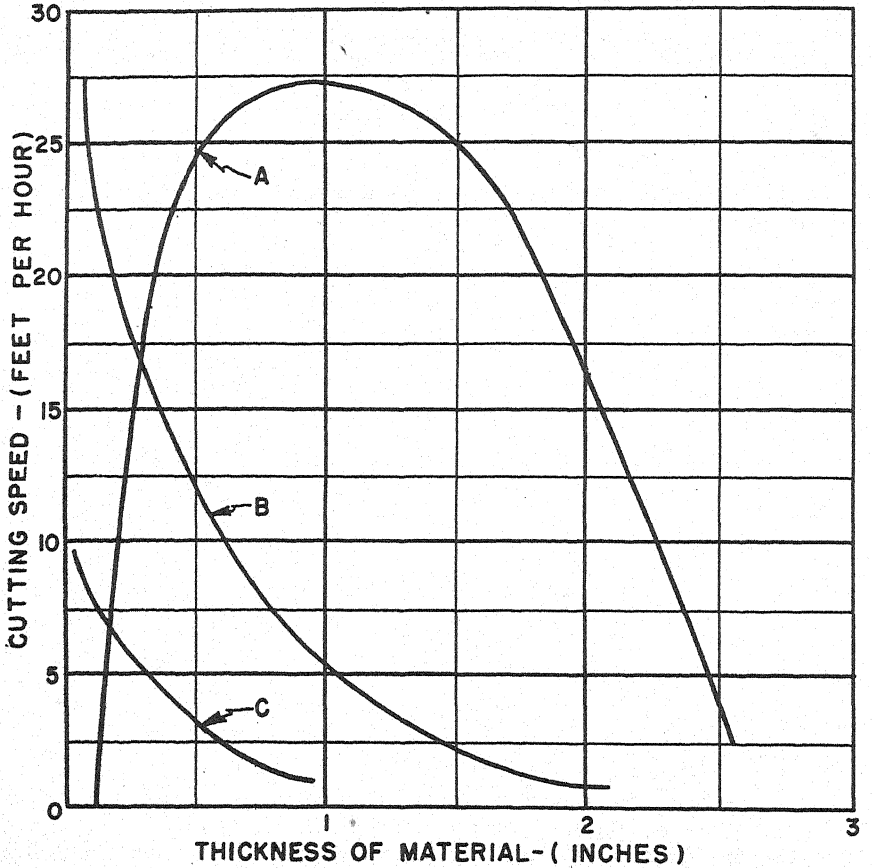
Fig. 2

Arc Cutting

As is the case with gas underwater cutting torches, electric arc torches for underwater cutting have been produced in a wide variety of types and forms. The electrodes used may be of carbon, graphite or metal and it is common practice to utilize direct current. In most cases the electrode is of tubular section in order to introduce a jet of oxygen into the molten crater created by the arc, thus causing combustion of the metal along with the melting action. A typical direct current carbon or graphite arc cutting torch is illustrated by Fig. 2.

In practical work the shape of the cross-section of the electrode used appears to be of little importance; however, the smaller the area of the cross-section the greater will be the speed of cutting with the same current, due, of course, to the greater current density. Carbon and graphite electrodes generally require a current of about 600 to 700 amp. and 70 v. for effective operation.

Underwater cutting can also be accomplished with covered metal electrodes using about 300 amp. Using waterproofed, covered steel electrodes, the cutting is accomplished by melting a kerf in the material to be cut. The speed of cutting and the consumption of the electrode are proportional to the current being used. Metal up to about 1 in. thick can be cut by melting a series of connected holes through it. A single operator



COMPARATIVE SPEEDS OF UNDERWATER ARC AND GAS CUTTING

Fig. 3

direct current arc-welding motor generator set of 300 amp. rating can be used for such work.

Comparative cutting speeds on medium steel by gas and arc underwater cutting torches are graphically shown by curves *A* and *B* of Fig. 3. Curve *A* represents the cutting speed of the oxy-hydrogen torch using a medium tip (one oxygen orifice, No. 45 drill size and four fuel orifices No. 52 drill size). Better results are obtained when using a tip having 6 fuel orifices. Curve *B* represents the average cutting speeds of three different arc cutting torches. Curve *C* gives the average cutting speeds of the same three arc torches for brass, cast-iron and stainless steels. These curves represent the performance to be expected with an experienced operator under ideal diving conditions, good visibility, no water current and a convenient position at a depth of about 8 ft. As can be seen by the curves, the arc torches are much more efficient on metal under $^3/_8$ in. in thickness than the gas torch. Also under adverse conditions involving poor visibility, the arc torches, not requiring flame adjustment, are more easily manipulated.

Underwater cutting is more or less difficult with either arc or gas cutting equipment. A diver always works under certain handicaps. The weight and bulk of his diving dress and the necessity of adjusting his air supply encumber his movements and require his constant attention. It is seldom that he can effectively see, so that most of his work must be guided by his sense of feel. Since it may be impossible for him to rig a platform or stage which will give him a solid footing, motion of the water due to currents may compel him to use most of his strength to hang on to keep himself from being swept away from his work. It is common practice to estimate that an experienced diver will require about five times as long to accomplish a task under water under the best conditions as it would take him to do the same work above the surface.

UNDERWATER ARC WELDING

Underwater arc welding may be accomplished using standard direct current arc-welding equipment having the exposed metal parts of the electrode holder well insulated, except the surfaces contacting the electrode. The electrodes used should be of the low carbon steel, covered, straight polarity type which have been given a waterproof coating. The material to be welded is more or less limited to medium steel, although emergency repairs have been made by attaching medium steel patches over holes in alloy and high carbon steel.

A 300-amp. single operator direct current arc-welding set will have ample capacity for this work since $^1/_8$-in. and $^5/_{32}$-in. electrodes appear to give the most satisfactory results under water using voltages about 10 v. higher and the currents about 15 amp. higher than those used above water. Often there is severe undercutting.

Straight polarity is used for underwater welding. In salt water reversed polarity causes rapid deterioration of any exposed metal part of the electrode holder. In any event all connections of the welding leads should be well insulated and waterproofed to reduce current leakage and electrolysis.

CHAPTER 17

CARBON STEELS AND IRONS*

Wrought Iron, Ingot Iron, Low Carbon Steel, Medium Carbon Steel, High Carbon Steel

Introductory

ONE of the important characteristics of commonly used commercial grades of wrought ferrous metals is the ease with which they can be joined by welding. In fact, the art of welding was developed with wrought iron and plain carbon steel.

Of the great tonnage of ferrous products that are being welded, the bulk of it has been with plain soft steels. Thus carbon steels are extremely important in any consideration of welding, both from technical and commercial viewpoints.

The selection of any material for welding depends primarily on the design of structure and service for which it is built, the required properties of the deposited metal and joints, the type of welding, the kind of filler metal, the conditions under which welding may, or must, be done, the qualifications of the operators available, the costs and the kind of testing that is required or is practicable.

For many years a special grade of soft steel was made for forge welding. Fusion welding, however, was largely developed with various kinds of soft steels without any special consideration of their weldability by these new processes that have become exceedingly important. Steel manufacturers now generally recognize the importance of welding quality and this is being given much more attention in the making of steel.

A.S.T.M. Specifications A-72–39, A-78–39 and A-89–39 may be considered typical of wrought iron and soft steel for the mechanical process of welding known as forge welding which, as is well known, was formerly largely used in general steel fabrication work.

Properly made rimming or semi-killed types of steel containing not over 0.22% carbon and not over 0.05% Ni or Cr are preferable for ordinary forge welding. It is essential that the metal form a readily fusible protective slag at a temperature well below the melting point of the metal. With such a slag, forge welds can be readily made at 2500°F. or lower. With the application of borax or other special fluxes, forge welds can be made

* Prepared by a committee consisting of N. L. Mochel, Westinghouse Elec. & Mfg. Co., *Chairman*; O. T. Barnett, Metal & Thermit Corp.; E. C. Bibber, Carnegie Illinois Steel Corp.; J. W. Bolton, The Lunkenheimer Co.; B. E. Field, Union Carbide & Carbon Res. Labs.; J. B. Fullman, A. M. Byers Co.

on higher carbon steels. The important function of fluid protective slags was generally known long before the advent of fusion welding. It seems remarkable that this principle was not applied at an earlier date in the development of fusion welding.

Fusion welding or resistance welding can be applied to steels of a wide range of compositions. In fact, all of the commercially produced carbon and low alloy carbon steels can be satisfactorily welded by one or more processes if the necessary care and precautions are observed in their treatment, and the most suitable facilities are used.

WROUGHT IRON

Description

Wrought iron is a two-component metal consisting of high purity iron base metal and iron silicate. The iron silicate takes the form of a glass-like slag. These two materials are in physical association, as contrasted to the chemical or alloy relationship that generally exists between the constituents of other ferrous metals. (See group P2-01 Table 5, Standard Qualification Procedure, Chapter 29.)

The iron silicate or slag content of wrought iron varies from about $2^1/_2\%$ to $3^1/_2\%$ depending upon the type or class of product. This constituent is distributed throughout the iron base metal in the form of threads or fibers which extend in the direction of rolling. The slag fibers are distributed so thoroughly throughout the iron component that there may be 250,000 or more to each cross-sectional square inch of finished material. This confers on the material a definitely fibrous structure which can be observed readily if a piece is nicked and fractured. Each of the two dissimilar materials that go to make up wrought iron has its own fusion temperature. The iron base metal, because of its low metalloid content, fuses at a temperature of about 2730°F., which is somewhat higher than the melting point of low and medium carbon steels. The slag component fuses at a temperature of about 2200°F., or several hundred degrees lower than the base metal.

The purity of the base metal gives wrought iron the ability to withstand higher temperatures than other ferrous metals and, in general, it should be worked hotter for best results. Also, the protection afforded the metal during heating by the fluxing action of the slag has a beneficial effect in producing sound welds. This is a particularly important factor in making plastic welds.

Wrought iron can be welded easily by any of the commonly used processes, such as forge welding, resistance welding, metallic arc welding, carbon arc welding and gas or oxyacetylene welding. The absence of the A1 point in wrought iron is of importance in reducing internal strains due to welding and in eliminating air-hardening capacity. However, internal strains cannot be eliminated as a factor and stress relieving of welded structures, particularly where heavy sections are involved, is considered good engineering practice today. Temperatures of 700 to 800° F. are usually sufficient to relieve stresses induced through expansion and contraction by the heat of welding. Stress relieving is particularly desirable for equip-

ment that is to be used in certain types of service, such as the handling of caustic solutions.

Table 1—Analysis of Wrought Iron, Per Cent

Carbon	0.05 or under
Manganese	0.05 or under
Phosphorus	0.10–0.15
Sulphur	0.04 or under
Silicon	0.08–0.15
Slag by weight	2.5 –3.5

Forge and Resistance Processes

When welding wrought iron by either the forge or the electric resistance methods, the important point to keep in mind is that the metal must be worked somewhat hotter than steel. In forge welding, for example, wrought iron is worked at what is termed a "sweating heat," which corresponds to a temperature of about 2500 to 2550°F.

When joining lengths of wrought iron pipe using resistance butt welds, the best results are obtained by forcing the ends together with pressure that is just sufficient to produce a sound union. Excessive pressure usually results in pronounced upsetting action which may cause a reduction in the strength properties of the joint.

Gas Welding

The procedure for welding wrought iron by the manual oxyacetylene process is practically the same as that followed in welding soft steel of the same thickness. However, one important point to keep in mind is that the iron silicate or slag included in the metal melts at a temperature which is below the fusion point of the iron base metal. The melting of the slag gives the surface of the metal a greasy appearance. This should not be mistaken for actual fusion of the base metal; therefore, heating should be continued until the iron is fully melted.

The best oxyacetylene welds are produced when perfect fusion is obtained without excessive mixing of the parent metal with the weld metal. Too much rubbing or agitation of the molten metal causes the formation of oxides which may be trapped in the weld. Ordinarily, just enough of the parent metal should be fused to provide a sound bond with the filler material.

The selection of welding rod metal is important. It is advisable to avoid rods containing high carbon or alloys solely intended to increase the strength of the deposited metal. Filler metal meeting the requirements of the latest revision of A.S.T.M. Designation A-251, Grades GA65 and GB65, may be considered suitable for welding wrought iron.

A neutral flame has been found to give the best results for gas welding wrought iron. In gas welding wrought iron in the thicker plates either a cascade or layer method of depositing beads produces the best results. For example, in the step-by-step method with $^5/_8$ in. thick plates the weld is started by depositing a root bead about $1^1/_2$ in. long. A second bead is deposited on this and extended about $1^1/_2$ in. beyond it, forming a new root bead. A third bead completes the weld for the first $1^1/_2$ in.,

forms a second bead for $1^1/_2$ in. and a root bead for another inch and a half. The weld is completed by a continuation of this process. In the layer method, beads of from $^3/_{16}$ to $^1/_4$ in. depth are used for the entire length of the weld.

Metal Arc Welding

In welding wrought iron by the metal arc process the best welds are produced when the welding speed and current are decreased slightly below those used for the same thickness of soft steel. This procedure is desirable because with reduced speed the pool of molten metal immediately following the arc is kept molten for a longer period of time, thus making for more complete elimination of the gases and affording the entrained slag an opportunity to float out of the weld metal. The slightly lower current value, particularly in welding thin sections, prevents burning through the material.

Excessive penetration into the face of the parent metal should be avoided. The penetration should be no greater than that required to obtain a sound bond between the deposited metal and the parent metal, because fusion of an excess quantity of the parent metal tends to carry slag into the weld metal.

Filler Metals.—In general, it is desirable to have the deposited weld metal as close in composition to the parent metal of wrought iron as possible. It should be recognized, however, that during the welding operation, the metal deposited undergoes a change in composition and some of the elements such as carbon, manganese and silicon, are lost through oxidation. Thus, the electrode should contain sufficient quantities of these elements to compensate for the loss during fusion so that the resultant weld metal will closely approach the base metal matrix of wrought iron as regards chemical composition. If an electrode were used which is practically identical to the parent metal, it is obvious that the deposited metal after undergoing melting would be apt to have a composition quite unlike wrought iron. This makes it undesirable to select an electrode which is initially extremely low in the elements mentioned above. It is suggested that electrodes selected for welding wrought iron be in accordance with the requirements of A.S.T.M. Designation A-233, Classification Nos. E6010, E6012, E6020 and E6030. This listing is not intended to indicate that other electrodes of similar composition are unsatisfactory but it includes specifications met by various electrodes which have been satisfactorily employed.

Carbon Arc-Welding Procedure

The carbon arc process has been used with very satisfactory results in welding wrought iron sections. The procedure is the same as that used for soft steel except that with the same travel speed the arc voltages and amperages should be slightly lower than those recommended for soft steel.

Physical Properties

In A.S.T.M. Specification A-42 are given the minimum longitudinal requirements for the physical properties of wrought iron plates produced by standard rolling operations. These are given in Table 2.

Table 2—Longitudinal Minimum Mechanical Properties of Wrought Iron Plates

Tensile strength, minimum psi.	48,000
Yield point, minimum psi.	27,000
Elongation in 8 in., minimum %	14

There is no difficulty in obtaining welds in wrought iron with physical properties equal to those of the base metal.

INGOT IRON

Ingot iron is an open hearth iron very low in carbon, manganese and other impurities.[1] Like most pure metals, ingot iron is soft and malleable. In general, ingot iron has a total metalloid content of less than 0.10% exclusive of copper which is considered beneficial wherever the ingot iron is scheduled for use as a corrosion-resisting material. Selected ingot iron with specified copper contents is available. A typical analysis of ingot iron is the following:[2]

Table 3—Typical Chemical Analysis of Ingot Iron

Element	Per Cent
Carbon	0.015
Manganese	0.035
Phosphorus	0.005
Sulphur	0.025
Silicon	0.003

As would be expected, the photomicrograph of ingot iron shows it to consist of pure ferrite as shown in Fig. 2. The basic composition is quite similar to wrought iron which has, in addition, the slag stringers seen in Fig. 3 which develop the well-known fibrous structure of wrought iron. Ordinary steel, as illustrated in Fig. 1, has dark pearlitic areas besides the white ferrite grains. Of course these darker regions occur as a result of the presence of an appreciable amount of carbon; some five to ten times that found in the ingot iron.

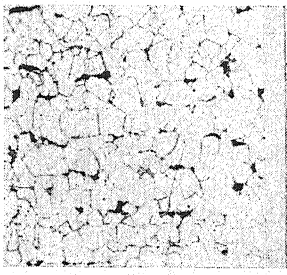


Fig. 1—Mild Steel

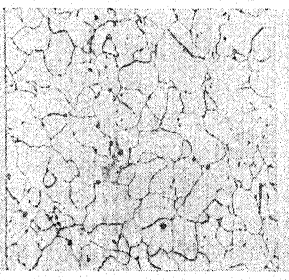


Fig. 2—Ingot Iron

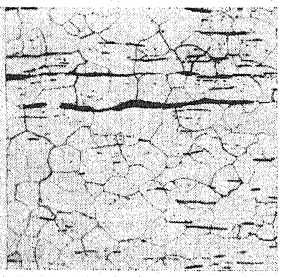


Fig. 3—Wrought Iron

Metals Handbook, 1939, American Society for Metals.
"Useful Information on Armco Ingot Iron," The American Rolling Mill Company.

In considering the welding of ingot iron, attention must be paid to the physical properties of the material as outlined in Table 4.

Table 4—Average Physical Properties of Ingot Iron

Ultimate tensile strength, psi.	45,000
Yield strength, psi.	30,000
Endurance limit (reverse bending), psi.	26,000
Per cent Elongation in 2 in.	35
Per cent Reduction in area	73
Modulus of elasticity	30,000,000

As it contains practically no carbon, ingot iron will not harden as the result of welding. No hardened heat-affected zone can exist. However, the welding fabricator should recognize the critical working range that appears between 1580° and 1920°F. Any hot fabrication should be done outside this range if checking or breaking is to be avoided. Because of its composition and very good ductility, ingot iron may be worked both at a white heat and at a dull red heat (below 1500°F.) without any trouble.

Because of purity, uniformity of grain structure and freedom from gas-forming metalloids, ingot iron possesses excellent welding characteristics. It may be joined by any of the common welding methods including the metallic arc process, the oxyacetylene method and resistance welding.

When metallic arc welding is employed, it is desirable to use coated electrodes. As ingot iron is an extremely pure iron, its melting temperature is somewhat higher than the commonly used impure irons, or steels. Consequently ingot iron must be worked hotter for the best results. To gain the increased heat, welding speeds are reduced slightly below those used for the same gage of mild steel.

Electrode choice may be made on the same basis as for mild steel. Where sheets (less than 1/8 in.) are to be welded, all-position electrodes may be specified. Where plates are being welded, the fluid down-hand electrodes find a place also.

Table 5 shows filler rod and electrode diameters for welding the various thicknesses of ingot iron. Deviation from these sizes may be found advisable under some conditions of welding.

Table 5—Electrode or Filler Rod Diameters Recommended for Various Thicknesses of Ingot Iron

Thickness of Plate	Electrode Diameter (Metallic Arc Method), In.	Filler Rod Diameter (Oxyacetylene) Method), In.
16 gage and lighter	1/16	1/16
16 gage to 1/8 in.	3/32 or 1/8	1/8
1/8 to 3/16 in.	5/32	5/32
3/16 to 1/4 in.	3/16	3/16
1/4 to 3/8 in.	1/4	1/4

Oxyacetylene welding is quite similar to the welding on low carbon steel by this method. Bare filler rods of the same analysis as the base metal will prove to be the most satisfactory. In a pinch shearings of the base stock may be used as filler metal although prepared rods are to be preferred.

Resistance welding includes all of the many types such as spot welding flash welding, butt welding, seam welding, etc. The higher melting point of ingot iron compared with mild steel, and the decidedly greater heat conductivity, indicate the need for greater welding heat.

CARBON STEEL

Steel is classed as carbon steel when no minimum content is specified or guaranteed for aluminum, chromium, columbium, molybdenum, nickel, titanium, tungsten, vanadium or zirconium; when the minimum for copper does not exceed 0.20%; and when the minimum content specified or guaranteed for any of the following elements does not exceed the amounts noted; manganese, 1.65%; silicon, 0.60%.

Low Carbon Steels (Carbon 0.30% or Under by Ladle Analysis)

For further definition of steels in this group see Table 5, Chapter 29, Standard Qualification Procedure, Group Pl-01.

A large part of the material in this HANDBOOK was prepared from the viewpoint of welding low carbon steels. It is therefore superfluous to devote much space to this material although it constitutes more than half of all the metals that are fabricated by welding. One of the important characteristics of the plain low carbon steels is the ease with which they may be fabricated by any of the welding processes. As to the steel itself, general information is given under Chapter 3, Weldability of Steels; Chapter 2, Metallurgy, and the welding features are covered under the respective processes of welding.

One general caution is needed in that welding in several codes is restricted to surrounding temperature conditions above 0°F. In cold weather (below 40°F.) it is desirable to preheat the start of the weld (within a radius of 3 in.) so that it is uncomfortable to the hand. It is assumed that the reader is familiar with other chapters such as Chapter 27, Filler Metal; Chapter 29, Standard Qualification Procedure; Chapter 32A, B, C on Design, etc.

Table 6 gives the chemical analysis of low carbon steel.

Table 6—Chemical Analysis of Low Carbon Steel

Carbon	0.06 to 0.30%
Manganese	0.35 to 0.90%
Phosphorus	0.05% max.
Sulphur	0.05% max.
Silicon	0.35% max.

Special attention is called to the A. W. S. Specifications for Highway and Railway Bridges (see Chapter 36B) wherein an attempt is made to restrict the chemistry with the knowledge that as thickness increases there will be slight reduction in the physical properties. Other specifications will undoubtedly follow this lead as the conceptions are basic from the welding viewpoint. In general, the physical properties of the weld metal and the zone adjacent to the weld in properly executed welds are equal to the base metal. See Chapter 34B, Impact Properties; Chapter 34C, Fatigue Properties; Chapter 34D, Corrosion.

Medium Carbon Steels (Carbon 0.30 to 0.45% by Ladle Analysis)

For further information on steels falling within this group see Chapter 29, Qualification Procedure, Table 5, Group P3-01.

This class of steel may be welded by the electric-arc, electric-resistance, gas and Thermit processes. The rapid cooling of the metal in the heat-affected zone produces a hard martensitic or troostitic structure. Therefore, it is desirable to hold the carbon as near 0.30% as possible. As compared with the unaffected base metal these hard areas are more brittle and difficult to machine. The cooling rate may be diminished and hardness decreased by preheating the metal to be welded to over 300°, preferably to 400°F. The required degree of preheating depends somewhat on the thickness of the section. Subsequent heating of the welded zone to 1100 to 1200°F. followed by slow uniform cooling will restore ductility and relieve internal stress.

The higher carbon and medium carbon steels necessitate proper consideration of the effect of the welding heat on the ductility of the affected zone. The first of the six factors that determine good welding practice for the medium carbon steels is the speed of welding (rate of advance of welding along the seam). With current conditions held constant, the slower the speed of welding, the less likely is a dangerous and brittle heat-affected zone.

The second point has to do with increased current. The greater the current with the welding speed held constant, the lower is the hardness of the heat-affected zone.

The third point considers the influence of the number of beads on the hardness of the heat-affected zone. Normally the first bead of a weld brings about the hardest heat-affected zone while multiple beads tend to temper or draw the hardness of the affected base metal zone thereby restoring some of the ductility that may have been removed by the first pass.

The fourth point considers the mass effect of the parent metal. The less the mass the more ductile the heat-affected zone because the autoquenching capacity of the parent metal is lowered.

The fifth factor is the increase in preheating. The higher the preheating temperature, or the higher the interpass temperature, the softer and more ductile is the heat-affected zone of the steel being welded. Proper preheating and interpass temperatures reduce the thermal gradient from hot to cold base metal sufficiently to avoid the formation of martensite.

The sixth and last point concerns the use of thermal insulation for the backing of the weld in order to retard the cooling rate. This practice, also, leads to a safer and more ductile structure in the heat-affected parent plate.

Of course the carbon content in the medium carbon steel groups is one of the controlling factors for dictating a satisfactory welding procedure. Some manufacturers recommend an electrode of the low carbon variety such as A.W.S.-A.S.T.M. E6010, E6012 and E6020.

In some instances the use of a special electrode such as the austenitic stainless steel type to put in the first beads either on the bottom of the joint or as the covering for the sidewalls represents good practice. Once the

joint is started with this type of electrode it is quite proper to complete the weld using an ordinary mild steel electrode. Armor plate welding, although not exactly suited for an example of this type of joining, is somewhat comparable and the use of the austenitic 25–20 electrode to prevent excessively hard heat-affected zones, while providing material of sufficient ductility, is well known.

Gas welds are made in medium carbon steels with the same procedures that are used for welding low carbon steels. As the steel at the joint is brought to fusion temperature the surrounding metal is heated in a zone of sufficient width to provide highly ductile steel to absorb stresses produced by expansion and subsequent contraction. Excessive hardness in the base metal adjoining the weld also is automatically avoided as a result of the absorption of sufficient heat in the steel surrounding the weld to prevent rapid cooling through the critical temperature. The ductility of both weld metal and affected base metal is increased if the weld is given a simple normalizing heat treatment. This can be applied by heating with the torch flame. A good method is to allow the weld to cool until black and then reheat to a uniform bright red, 1550°F. for example, and cool naturally in air. This heating generally can be made to remove the stresses produced by irregularity of cooling that results when a seam is welded.

The completed weld should equal or exceed the base metal in strength and stiffness in which case yielding under heavy loading or other severe conditions of service will occur in the base metal. This high strength is generally obtained in gas welds in medium carbon steel by using low alloy steel welding rods. The small amount of alloy in the weld will serve to compensate for carbon or other strengthening elements that are removed from the steel which is melted.

High Carbon Steels (Carbon 0.45% or Over by Ladle Analysis)

These steels are rarely welded except in special cases and in thick sections. The tendency for the metal heated above the critical range to become brittle is, of course, much more pronounced than with lower or medium carbon steel. Therefore, thorough preheating of metal in and near the welded zone to at least 400°F. is essential. Subsequent annealing at 1350 to 1450°F. is also desirable.

Rail joints fall in this class of steel and to them several of the welding processes are commonly applied.

The arc process may be used to fill up worn parts in medium or high carbon steels, preferably with the shielded electrodes. For some applications, mild steel filler metal will serve; in others, special higher carbon filler metal is used. Filler metal containing high manganese is preferable for such work.

Preheating at high temperatures, maintaining the interpass temperature and post heating before the weldment has had a chance to cool to room temperature are recommended procedures. Once more the selection of an electrode with low penetrating powers and adequate fusion properties such as those of the A.W.S.-A.S.T.M. Classification grade E6012 is a good choice. The use of a wider scarf, along with the facing of this scarf with austenitic stainless steel, proves quite advantageous in the welding of the high carbon steels.

Gas welds are made in high carbon steels both for the general purposes of joining two or more parts and for the repair or replacement of worn metal. The fact that high carbon steel is more sensitive to overheating and burning than medium or low carbon steel makes it desirable to keep to a relatively small pool of melted metal. This may be accomplished in welding a steel object of considerable thickness by first preheating and then welding with a smaller flame than would be required if the preheating were not employed. By this means the welding can be advanced steadily and the melted metal can be covered constantly by the protective envelope of flame which will exclude the harmful atmosphere. A welding procedure that will avoid severe stresses should be aimed for. Sometimes this condition and the desired limitation of the size of the pool of melted metal can be secured by simultaneous vertical welding of a double vee groove with two torches. This practice is followed in butt welding of railroad rails, for example. It is even more important in the case of high carbon than of low carbon steels to use alloy-containing welding rods. In some cases high carbon steel is welded with austenitic steel rods and if desired, with the carburizing flame technique. The austenitic rods melt at a lower temperature than the steel base metal and the carburizing flame technique permits complete union at minimum welding temperature with practically no fusion of base metal into the weld. When commercial rods are to be used for welding high carbon steel the carburizing flame is desirable for it permits the welding to be carried out at a lower temperature while carbon absorbed in the molten metal from the flame increases the strength of the weld as compared with that secured from the same welding rods when a neutral welding flame is used. For applications in which bronze welds will provide the necessary strength, welding with bronze rods is also used as a means of producing a joint without overheating the high carbon steel. Considerable increase of ductility in gas welds in high carbon steels is secured by a normalizing heat treatment which is generally applied locally with a torch flame.

Thermit welding of high carbon steels as found in railroad rails and steel mill rolls is common practice. The special properties of the weld as well as the techniques employed are well adapted to the welding of high carbon steel as well as the medium and low carbon steels treated earlier in this chapter.

CHAPTER 18

LOW ALLOY STEELS*

Effects of Alloying Elements, Weldability, Welding Technique, Low Alloy High-Strength Steels, Low Alloy Steels for High-Temperature Service, Analyses and Properties of Typical Low Alloy Steels.

THE low alloy steels are pearlitic steels consisting of grains of ferrite or alpha iron in which carbides are distributed, the grains being of variable size and the carbides possessing wide variations in size, form, amount and distribution, dependent upon steel composition and previous mechanical and thermal history. The physical properties of a steel of given composition are dependent upon the grain size of the ferrite and upon the amount, distribution, form and size of the carbide constituents. Added alloying elements change profoundly the physical properties of a steel of given carbon content by one or more of the following effects upon the ferrite grains and carbides: (*a*) by solid solution hardness; that is, increase in the hardness or strength of the ferrite by solution of the alloying element in the ferrite grains; (*b*) by refinement of grain size; (*c*) by changing the nature and distribution of the carbide constituent; (*d*) by conferring greater hardenability to the steel on cooling from above critical range temperatures; and (*e*) by precipitation hardening; that is, strengthening of the ferrite by precipitation of constituents as "keying" particles along the slip planes of the ferrite. Important secondary effects, such as deoxidizing or scavenging of the steel melt, may be obtained, but these need not enter the discussion.

In addition to carbon, nine alloying elements are in common use in the compounding of low alloy special steels—*chromium*, *copper*, *manganese*, *molybdenum*, *nickel*, *phosphorus*, *silicon*, *tungsten* and *vanadium*. Restricted use of *aluminum*, *columbium* and *titanium* is made in some of the low alloy steels for elevated temperature service. These elements are added in such steels for the purpose of increasing oxidation resistance and of reducing hardenability.

Solid solution hardness is the primary effect of some of these elements. Other elements will act principally by their effect on the carbide constituent or by their influence in promoting small grain size. Practically all elements possess multi-effects, changing the physical properties by a combination of one or more of the enumerated microstructural phe-

* Prepared by a committee consisting of J. H. Critchett, Union Carbide and Carbon Research Labs., *Chairman;* T. N. Armstrong, International Nickel Co.; R. W. Emerson, Pittsburgh Piping and Equipment Co.; J. C. Hodge, Wellman Engineering Co.

Table 1—Methods by Which Alloying Elements Increase Strength of Steel

(Elements arranged according to relative intensity of their effects)

A—Solid Solution Hardness:

(1) Phosphorus
(2) Silicon
(3) Manganese
(4) Nickel
(5) Chromium in excess of that required to form carbides
(6) Molybdenum in excess of that required to form carbides
(7) Vanadium in excess of that required to form carbides
(8) Tungsten in excess of that required to form carbides
(9) Copper

B—Refinement of Grain:

(1) Vanadium
(2) Molybdenum

C—Carbide Nature and Form:

(1) Vanadium
(2) Chromium
(3) Molybdenum
(4) Manganese
(5) Tungsten

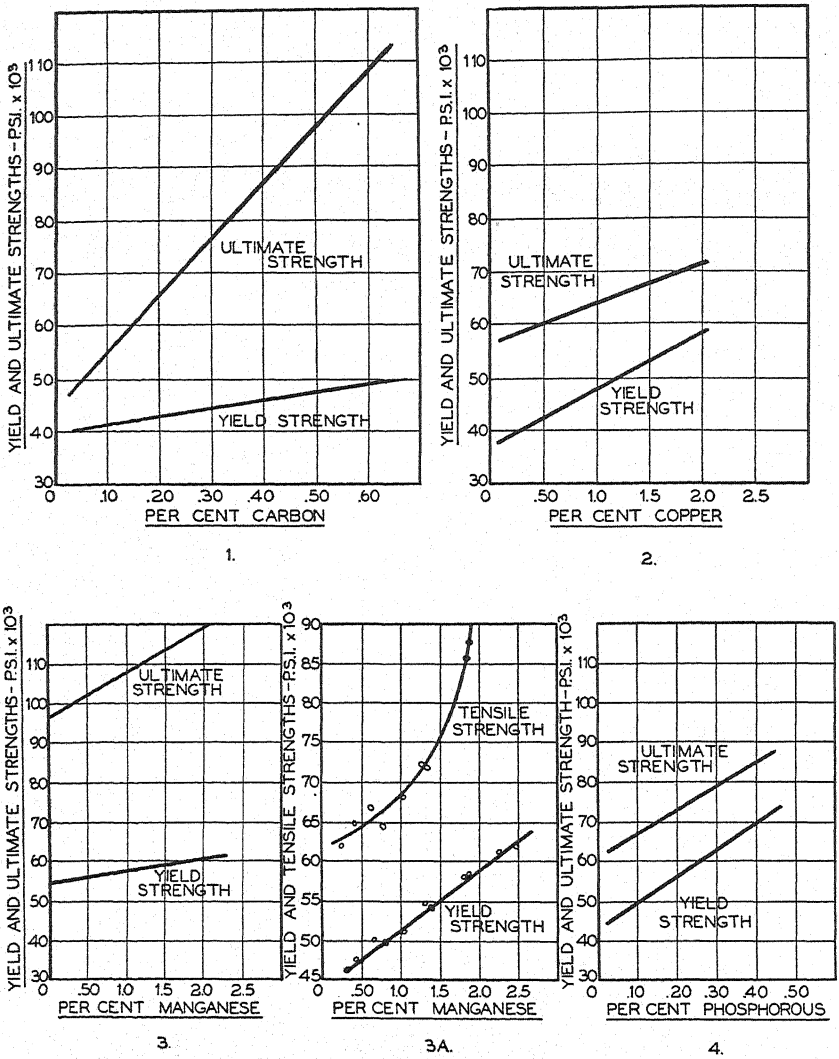
D—Hardenability on Cooling from Above Critical Range:

(1) Carbon
(2) Manganese
(3) Chromium
(4) Molybdenum
(5) Vanadium
(6) Tungsten
(7) Nickel
(8) Silicon

E—Precipitation Hardening:

(1) Copper

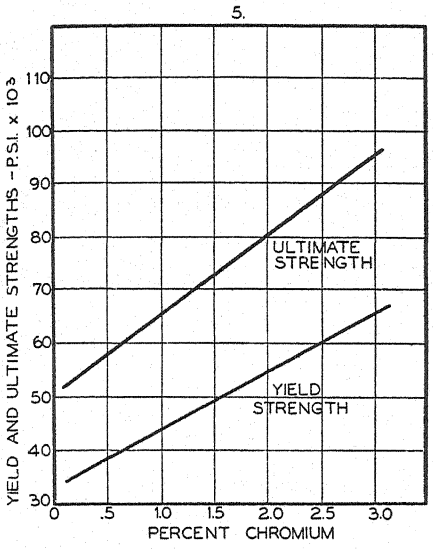
nomena. Table 1 presents a grouping of the alloying elements as to methods whereby increase in hardness is attained, the elements in each group being arranged according to the relative intensities of their effects. Consideration of the important effect of impurity elements (nitrogen and oxygen) is not presented in the table.

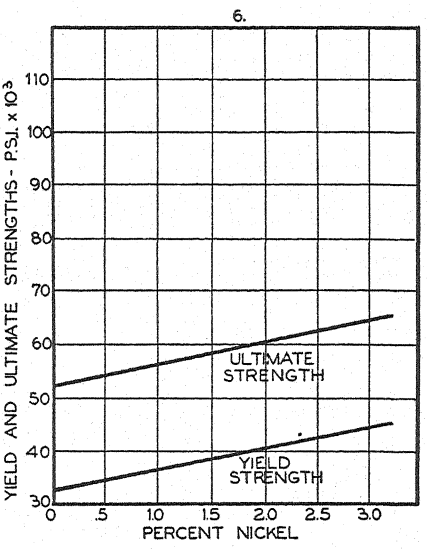


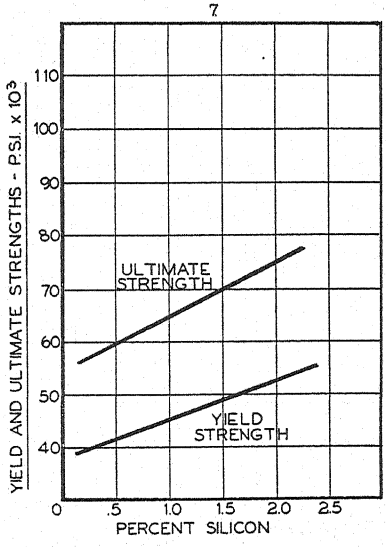
1. Fe-C (*Nead*). Spreading lines.
2. Fe-Cu (*Breuil*). Parallel or converging lines.
3. Fe-Mn (*Bain*) for 0.55% C steel. Spreading lines.
3a. Fe-Mn (*Lang*) for low-carbon steel. Spreading lines.
4. Fe-P (*d'Amico*). Parallel or converging lines.

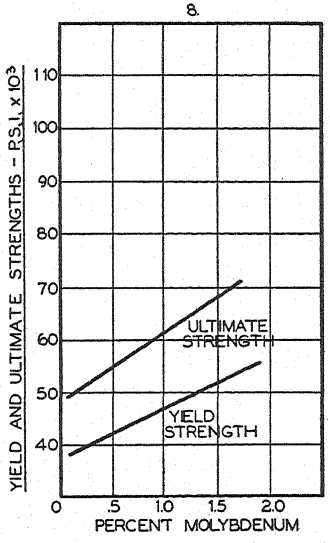
Fig. 1—Effect of Adding Various Elements on

The various methods by which the added alloying elements accomplish increased strength and hardness are presented for each element in Table 2, the effects being arranged in order of their relative importance (based on usual amounts of the alloys present).









5. Fe-Cr (*Wright and Mumma*). Spreading lines.
6. Fe-Ni (*International Nickel Co.*). Parallel or converging lines.
7. Fe-Si (*Paglianti*). Spreading lines.
8. Fe-Mo (*Hadfield*). Spreading lines.

Yield Strength and Tensile Strength of Iron
(Epstein, Nead and Halley)

The addition of the various alloying elements produces effects other than increased strength and hardness. Increased yield strength is obtained (Fig. 1), some of the elements being particularly effective in increasing the yield strength without unduly increasing the tensile strength. *Copper*, *phosphorus*, *nickel* and *silicon* have been reported as being more effective than other elements in securing a high elastic ratio (yield strength divided by tensile strength).

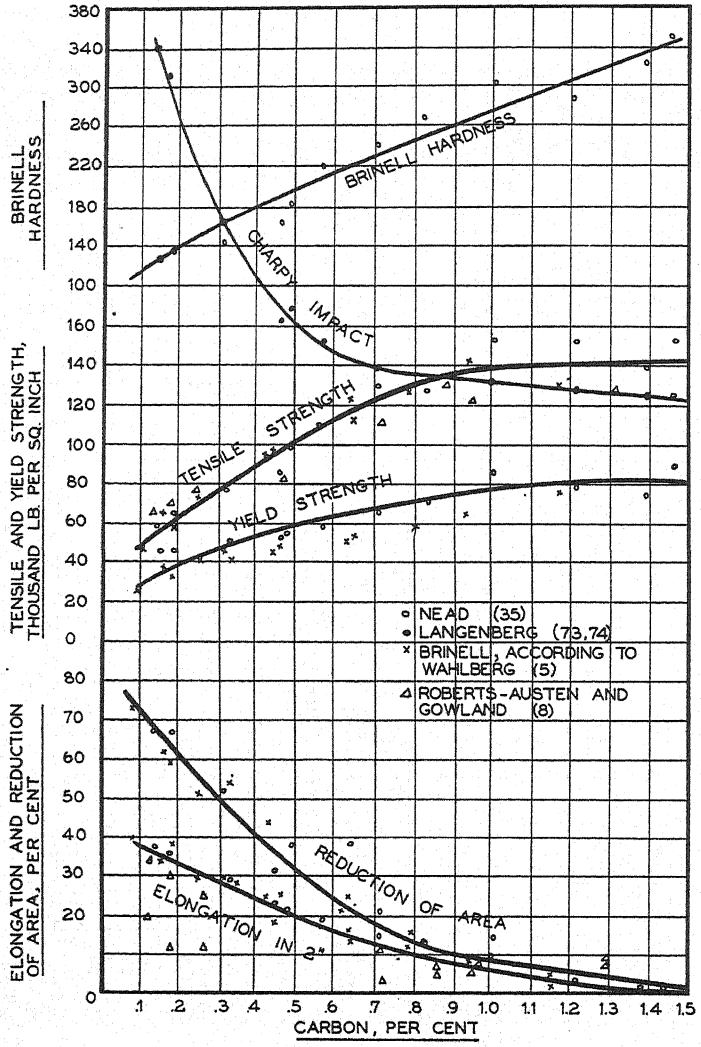


Fig. 2—Effect of Increasing Carbon Content on Mechanical Properties of Hot Worked Steels
(Alloys of Iron Research—Sisco)

Table 2—Methods by Which Individual Elements Confer Increased Strength to Steel

Carbon	1 Hardenability (p)			
Manganese	1 Hardenability (p)	2 Solid solution (p)	3 Carbide effects (m)	
Chromium	1 Hardenability (p)	2 Carbide effects (p)	3 Solid solution (m)	
Tungsten	1 Hardenability (p)	2 Carbide effects (p)	3 Solid solution (m)	
Molybdenum	1 Hardenability (p)	2 Carbide effects (s)	3 Hardenability (s)	Solid solution (m)
Vanadium	1 Hardenability (p)	2 Carbide effects (s)	3 Hardenability (s)	Solid solution (m)
Nickel	1 Solid solution (p)	2 Hardenability (s)		
Silicon	1 Solid solution (p)	2 Hardenability (m)		
Phosphorus	1 Solid solution (p)			
Copper	1 Precipitation (p)	2 Solid solution (m)		

(p)—Primary Effect.
(s)—Secondary Effect.
(m)—Minor Effect.

Increased strength is accompanied by a decrease in ductility. The low alloy steels provide, however, a higher ductility for a given tensile strength than a plain carbon steel of equivalent tensility. An increase in tensility by increase in *carbon* content alone results in a serious decrease in ductility and toughness (Fig. 2) by reason of corresponding increase in the amount of cementite, the non-ductile carbide constituent. However, the increase in strength of the low alloy steels may be accomplished by the various microstructural effects previously outlined without necessarily introducing excessive amounts of hard, brittle constituents.

Important beneficial auxiliary effects, such as increased corrosion resistance, result from the presence of some of the alloying elements. In some cases the elements may be added primarily for such specific effects rather than for increase in tensile properties. Enhanced corrosion resisting qualities may be imparted to the steel by *copper, chromium, nickel, phosphorus,* and *silicon* additions. *Small additions of vanadium* will counteract the loss in ductility and brittleness of steels of manganese contents above 1 or $1^1/_4\%$. At elevated temperatures, that is, above approximately 950°F., where resistance to oxidation is necessary, the elements *aluminum, columbium, chromium, silicon* and *titanium* are beneficial and, in the temperature range where flow by plastic yielding under service stresses is the dominant phenomenon, increased creep resistance is attained by *molybdenum, tungsten,* or *vanadium* additions and also, as recently reported, by *phosphorus* additions. In the low temperature field, for subzero temperatures, some of the low alloy steels may retain normal notch toughness, which is lost by plain carbon steels at such temperatures. This is attained by toughening of the ferrite: (*a*) by *nickel* or *chromium-copper* additions; (*b*) by incidental superior deoxidation practice in the manufacture of alloy steel; or (*c*) by finer grain structure.

The above brief consideration of the effects of the various added alloy elements in low alloy steels has been presented since they largely determine the choice of a particular analysis for special purposes. The various special analyses have been selected to provide optimum physical and chemical properties to meet a given set of service conditions, with ease of fabrication, including welding, an important consideration.

The Metallurgy of Low Alloy Steels as Related to Weldability.—If the thermal conditions of a welded joint during a welding cycle are considered, it is immediately apparent that hardenability of the alloy steel weld metal and parent metal becomes the dominant factor in the application of welding to low alloy steels. In many welding processes relatively small volumes of molten weld metal are deposited in the joints adjacent to comparatively large masses of relatively cold parent metal. Immediately after deposition the weld metal is rapidly cooled from the solidification temperature. Similarly the affected zone of the parent plate material which has been heated to varying temperatures, resulting in a thermal gradient from the melting temperature at the line of fusion to normal temperature at some distance from the joint, is also rapidly cooled. The rate of cooling of the weld metal and of the heat-affected zone of the parent metal will vary considerably depending upon a number of variable factors, such as (1) the thermal capacity of the parent metal, which varies according to size, thermal conductivity and its temperature before start of welding operations, and (2) the heat input of the welding process used.

The effect of cooling rate and alloy composition may be best appreciated by consideration of Fig. 3, the diagram showing the structural constituent generally resulting from cooling a steel of known alloy and carbon contents from above the critical range. The effect of increasing rates of cooling is to depress the lines of demarcation of the various structural zones toward the lower left-hand corner of the diagram. It is evident that increasing the rate of cooling or increasing the amounts of carbon or hardening alloying elements will tend to produce pearlitic, sorbitic, troostitic or martensitic conditions which represent increasingly hard and

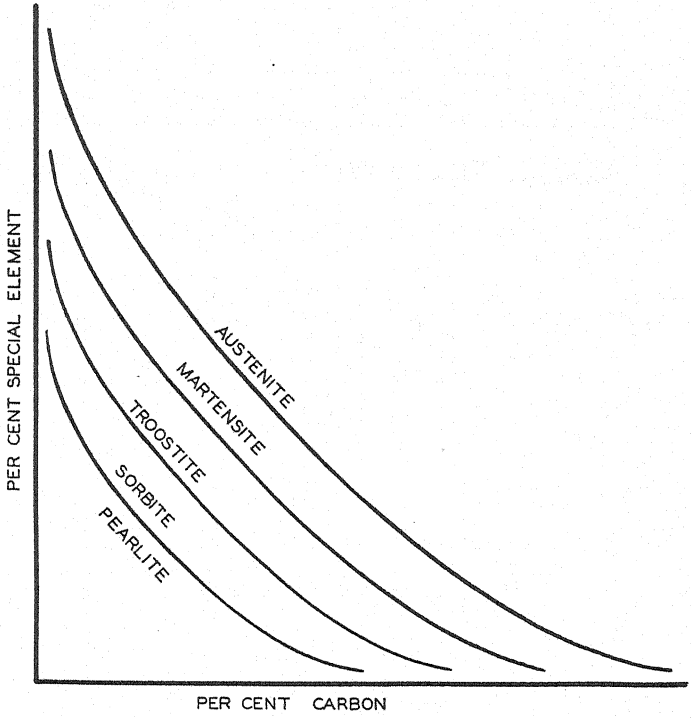


Fig. 3—Constitutional Diagram
(Sauveur)

brittle structures.* This is due to a depression of the temperature at which the gamma to alpha transformation occurs. The depression of the transformation temperature as influenced by cooling rate is illustrated in Fig. 4 for a 0.85% carbon steel. The effect of an alloying element in depressing the gamma to alpha transformation temperature, and thus conferring hardenability to the steel, is illustrated by the dilatation curve of an air-hardening alloy steel as compared with the dilatation curve of a non-air-hardening steel (Fig. 5).

To withstand the deformations resulting from the localized contraction

* This conception of the production of the various microstructural conditions is not in accordance with a recently advanced theory. The older and more established terminology is used in this discussion.

of weld metal during welding operations, the formation of hard, brittle constituents, such as troostite and martensite, should be avoided. Their presence usually results in cracking of the weld. The transformation from austenite to ferrite or from gamma to alpha iron is accompanied by a considerable increase in volume, which in welding is localized in the weld metal and in the affected zone of the plate material which has been heated above the critical range. This change in volume is of no great importance if it occurs at elevated temperatures when the material is somewhat plastic, but becomes of increasing importance in establishing stresses as the critical temperature is depressed. The hard constituents

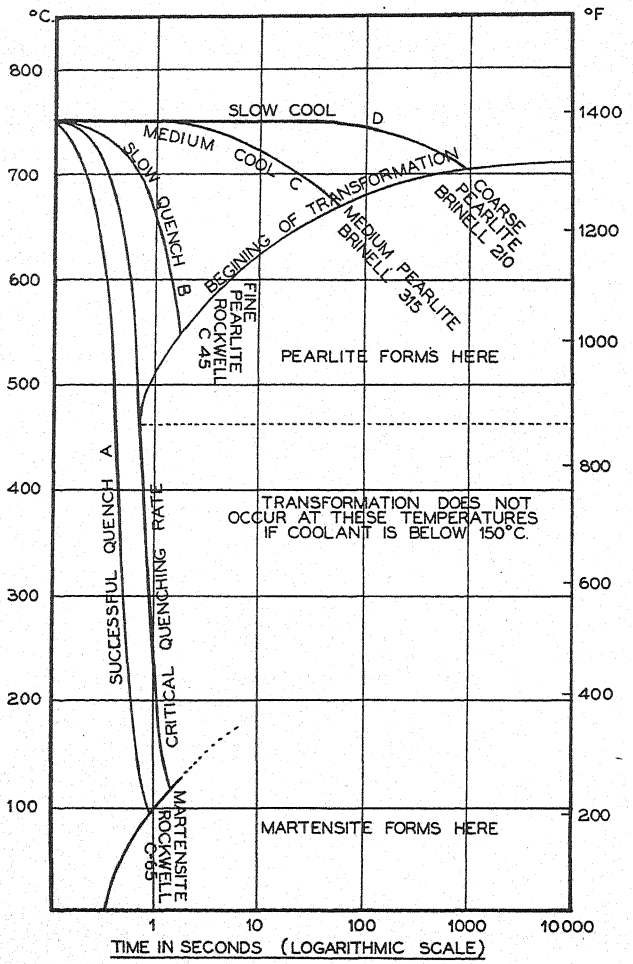


Fig. 4—Influence of Cooling Rate on Temperature and Product of Transformation in a 0.85% Carbon Steel
(E. C. Bain)

resulting from depression of the transformation temperature cannot accommodate the movement necessary for relief of the stresses established by the change in volume during the transformation and cracking of the weld results.

The factors tending to produce hard and brittle structures in the weld zone of a steel are, therefore, rapid rates of cooling and the presence of critical amounts of alloying elements which confer hardenability to the steel. Factors tending to inhibit hardenability and resultant cracking are the reverse; that is, a slow rate of cooling from welding temperatures and a reduction in the amount of hardening alloying elements.

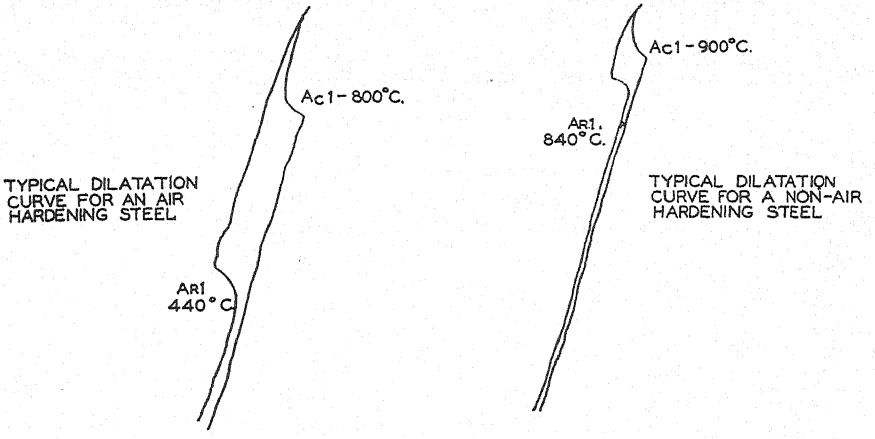


Fig. 5—Typical Dilatation Curves of an Air Hardening and of a Non-Air Hardening Steel

Weldability—Composition of Base Material

Weldability may be defined as the ability of a steel to pass through the thermal cycle of a particular welding process without the production of hard or brittle zones in the welded joint, which would tend to the production of cracks during the welding of a particular structure or to failure of the welded joints under service loading of the structure. Steels of different compositions but with equivalent hardness may possess different degrees of toughness or brittleness, so that the hardenability of a steel is not exactly synonymous with its weldability. Weldability will be maintained by keeping to a minimum those alloying elements which confer pronounced hardenability.

Carbon Content.—Since carbon exerts the most pronounced hardening effect, its content in the readily weldable low alloy steels should be limited, generally to a maximum of 0.15%. In plain carbon steels without the additive effects of alloying elements a carbon content of 0.25% will produce a sorbitic structure in the affected zone of a metal arc weld made without

preheating. With the usual amounts of manganese and silicon present in plain carbon steel, a carbon content of 0.35% is the maximum which may be safely used for large welded structures, and it is generally held that a large welded structure of plain carbon steel of this carbon content should be subjected to a stress-relieving treatment. Plain carbon steels with carbon contents in excess of 0.35% may be welded provided special precautions are taken, such as preheating. The above limit of 0.15% carbon indicated for the easily weldable low alloy steels cannot be applied to all compositions. It will vary from this value in both directions dependent upon the amount of additive alloying elements present, particularly those which are quite effective in conferring hardenability, such as manganese and chromium. A logical procedure in the selection of a carbon content for a particular composition would be to lower the carbon content of large rigid structures which cannot be subjected to a stress-relieving treatment; higher carbon contents may be permitted for structures which can be stress-relieved, and still higher carbon contents for structures which can be preheated prior to welding and stress-relieved after welding. This

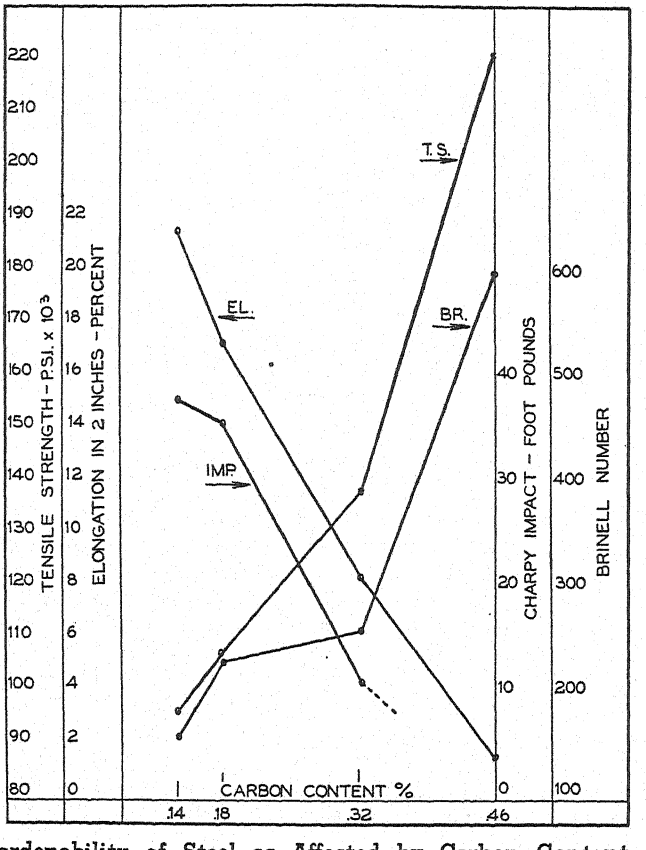


Fig. 6—Hardenability of Steel as Affected by Carbon Content—Physical Properties of Steels of Various Carbon Contents Water Quenched from above Critical Temperatures

same consideration may also be applied with respect to the quantities of alloying elements which may be present.

WELDING TECHNIQUE

Welding Processes.—The rate of cooling from welding temperature and hence the hardness attained in the weld for a given composition of steel will vary with the welding process employed. At one extreme are the steep thermal gradients occurring in resistance welds, such as spot welds made in short-time welding intervals, where the cooling rate after welding is extremely rapid. At the other extreme low thermal gradients characterize the gas welding and Thermit welding processes with accompanying slow cooling rates. Between these two extremes the various arc-welding processes occupy an intermediate position with rates of cooling approaching those of the resistance welding processes. The welding processes may, therefore, be listed with respect to ameliorating the tendency to weld hardening of the low alloy steels: (*a*) Thermit or gas welding, (*b*) arc welding and (*c*) resistance welding. Example: Chrome molybdenum steel, S.A.E. 4130X, is successfully acetylene welded for aviation tubular structures but is usually not resistance spot welded due to the hard, brittle welds produced in this particular steel by the instantaneous cooling of spot welding.

The rate of cooling after welding may, of course, be retarded by the further application of heat immediately after welding. This can be more readily accomplished in certain welding processes than in others, as, for example, in gas welding or in resistance butt welding.

The above discussion relates only to heat effects of the various welding processes, and other considerations may naturally govern the selection of a process for welding a structure of low alloy steel composition.

Aside from their weld-hardening effects, alloying elements in steel in even minor quantities may seriously interfere with the production of sound welds in certain welding processes. Readily oxidizable elements, such as aluminum, chromium, silicon and titanium will produce in resistance butt welding operations an infusible oxide film, which prevents complete fusion, and special precautions are necessary to assure 100% welds.

Preheating.—The rate of cooling from welding temperatures may be most conveniently retarded by preheating of the parts to be welded. For steels possessing relatively high hardenability on air cooling, preheating becomes a necessity, especially with the metal arc welding process with its extremely localized application of heat. Preheating is, of course, accomplished coincidental with welding operations in both acetylene and Thermit welding processes. Preheating cannot in general be applied to large structural members, so that for the low alloy high-strength constructional steels weldability has been maintained by keeping at a minimum the amounts of elements with pronounced hardening characteristics. The necessary preheating temperature will vary from a slight preheat of 50 to 100°F. in the case of compositions of low carbon, low alloy contents to a maximum of 400 to 600°F. in the case of the higher carbon low alloy steels or in the case of the steels having alloy contents toward the upper limit of

the range, as, for example, the chrome-molybdenum steels with chromium contents approaching 5%, such as are used for high temperature service.

Electrodes and Welding Wire.—The requirements for electrodes and welding wire will vary considerably with the anticipated service of the welded structure. Where strength alone is required, plain carbon steel electrodes of the usual commercial types may be satisfactory, since the usual plain carbon steel weld metals normally possess a relatively high yield point and tensility. In depositing such electrodes in joints between low alloy steels, especially on relatively thin sections where the volume of added weld metal from the electrode is slight in comparison with the total volume of fused metal, a considerable alloy pickup is obtained from the parent plate material, which further enhances the yield point and tensile strength of the weld metal. Tensile strengths of approximately 70,000–80,000 psi. may be obtained with plain carbon steel electrodes. For higher tensile strengths, electrodes of $^1/_2$% molybdenum steel have been extensively used for a wide variety of low alloy steel compositions, producing tensile strengths in the weld metal approaching 100,000 psi. Electrodes are available which will deposit weld metal of the same approximate chemical composition as the parent metal and this arrangement should generally be followed. This is especially true if other beneficial properties of the parent metal are to be obtained in the welded joints, such as superior corrosion resistance, creep resistance or low temperature notch toughness.

Heat Treatment.—The necessity for heat treatment after welding will vary depending upon the alloy steel being welded, the dimensions of the structure and the service to which the welded structure will be subjected. For low alloy structural steels where weld hardening is only slightly greater than in mild plain carbon steel, rules governing the stress relieving of the plain carbon steel will be applicable. When the air or weld hardening becomes more marked the necessity for stress relieving becomes proportionately greater and becomes mandatory for steels where the alloy content is toward the high end of the selected range of alloy additions, as, for example, the 5% chromium steels used for pressure parts at elevated temperatures.

Stress relieving is accomplished by a thermal treatment, during which the yield point of the steel is reduced to a value which permits plastic adjustment of the steel. The low alloy steels generally possess high yield points at stress-relieving temperatures, higher than plain carbon steels. A more efficient stress-relieving treatment is required to reduce the residual stresses of a welded low alloy steel to the same degree as is attained on stress relieving a carbon steel welded structure by the usual stress-relieving cycle, that is, 1100–1200°F. for one hour per inch of thickness. In the case of the air-hardening steels, such as the chrome-molybdenum steels for elevated temperature service, the stress-relieving temperatures must be considerably higher to eliminate the hard structures in the weld. A full anneal from above 1450°F. or a longer time at approximately 1350°F. is generally practiced. Such heat treatments at higher temperatures result in an appreciable lowering of the tensile strength, but in the case of these special steels the desired property is increased creep value or oxidation resistance at elevated temperatures rather than room temperature tensile strength.

In selecting for the structural high-strength steels a stress-relieving cycle, that is, temperature and time at temperature, care should be taken that the thermal cycle is not sufficiently drastic to seriously reduce the originally high yield point and tensile values of the parent metal or weld metal (Example—Table 4).

Copper bearing steels in excess of approximately 0.60% are susceptible to "precipitation hardening" on reheating them to approximately 900–950°F. after normalizing treatment. Steels containing approximately 1% copper will show after "precipitation hardening" treatment an increase in tensile strength of 20,000 psi. A number of the low alloy high-strength structural steels contain copper within the range of 0.50 to 1.50%, added primarily for increased corrosion resistance. It has been proposed that welded structures involving these steels be strengthened by subjecting them to a normalizing treatment and to a "precipitation hardening" treatment at 900–950°F. This practice cannot be generally accepted, since a structure so treated cannot be subsequently reheated without weakening the structure within the reheated portions. Re-normalizing and re-drawing at 900 to 950°F. would be necessary to restore the strength of the reheated structure to the value originally obtained by "precipitation hardening."

LOW ALLOY HIGH-STRENGTH STEELS

Group I—Manganese-Silicon Base Steels

Silicon Structural, Sil-Ten and Hi-Tensile Plate are similar in chemical composition, their higher strength being obtained by increase in carbon, manganese and silicon over the usual amounts present in 55,000 or 60,000 psi. structural carbon steel. Since the desired high-tensile properties cannot be obtained without approaching the high end of the carbon range, their weldability is somewhat limited, with a tendency to cracking on welding large sections. Stress relieving of welded structures involving heavy sections is generally necessary.

Standard specifications for the Hi-Tensile Boiler Plate have been adopted by both the A.S.T.M. and the A.S.M.E. Boiler Code and this steel has been widely used for pressure vessel and boiler drum construction. The most interesting example of this modified carbon high-strength steel, effecting an enormous saving in weight of structure, is the fusion welded high pressure penstock piping of Boulder Dam, where design requirements were based on a ratio of 2:1 between yield strength of the steel and working stress. Nominal working stress being 18,000 psi., a steel with a minimum yield strength of 38,000 psi. was required. This was impossible of attainment with the usual 55,000 psi. boiler plate, but was readily secured with the modified analysis either in the as-rolled condition or after a grain refining normalizing treatment. Large numbers of boiler drums of this steel have since 1934 been fabricated by fusion welding, the higher strength 70,000 psi. plate material being used today to the practical exclusion of the 55,000 tensility boiler plate, at least for the heavier drums.

The last three steels of this group, Granite City H.S. 1, Carbon-Molyb-

Table 3—Analyses and Physical Properties of Commercial Low Alloy High-Strength Steels

GROUP I—MANGANESE-SILICON BASE STEELS (Manganese less than 1%)

	1 SILICON STRUCTURAL	2 SIL-TEN	3 HI-TENSILE PLATE	4 GRANITE CITY HS1	5 CARBON MOLYBDENUM (0.25%)	5½ N-A-X HIGH TENSILE
Manufacturer	.....	U. S. Steel	.....	Granite City Steel Co.	.....	Great Lakes Steel Corp.
Specification (standard)	A.S.T.M. A-94	...	A.S.T.M. A-212	.....	.....	....
	.....	...	A.S.T.M. A-212	.....	.....	....
ANALYSIS:						
Carbon	0.40 Max.	0.20–0.40	0.35 Max.	0.14	0.10–0.20	0.10–0.18
Manganese	1.00 Max.	0.40–0.80	0.90 Max.	0.70–0.90	0.70–0.90	0.50–0.75
Silicon	0.20 Max.	0.20 Min.	0.30 Max.	0.15–0.20	0.20–0.30	0.70–0.90
Copper	*	0.25 Max.	*	0.30 Max.	†	0.25 Max.
Special elements	...	...	...	Cr 0.12†	Mo 0.20–0.30	Cr 0.50–0.65
	...	...	...	Mo 0.10†	...	Zr 0.10–0.20
PHYSICAL PROPERTIES (AS-ROLLED):						
Yield point, psi.	45,000 Min.	45,000	35–45,000	70,000‡	33–45,000	50–65,000
Tensile strength, psi.	80–95,000	90,000	70–82,000	80,000‡	60–80,000	70–85,000
Elongation in 2 in., %	...	18.0	...	...	...	50–32
Elongation in 8 in., %	...	...	...	19.0	...	...
Red. of area, %	...	...	...	...	...	74–60
Hardness	...	...	...	90 Rb	...	...

* Copper up to 0.25% may be present.
† Optional.
‡ A certain degree of cold working may be necessary to obtain these values. Values are for wire or sheets.

denum (0.25%), and N-A-X High Tensile weldable steels are low in carbon and also in the amount of added alloying elements. Their weldability is approximately the same as that of mild steel.

Group II—Medium-Manganese Base Steels

All of the steels in this group contain manganese in excess of 1.0% and since this element's hardening power is great, the carbon content should be kept very low for ready weldability. A carbon limitation of 0.13 or 0.15% maximum would be desirable for structures which cannot be stress-relieved, this being approached by steels 8 and 9, both of which have been designed with welding in view.

Steel 12, Cromansil, has a variable carbon range, the carbon being selected according to necessary properties for the service of the structure, but for welding grades this same limitation as to carbon content applies. Where the structure can be stress-relieved, higher carbon contents up to 0.25 or 0.30% may be permitted. This steel is one of the more popular high-strength steels and has been extensively used in a variety of welded structures. Its use in the lower tensile range (lower carbon) has been sanctioned for welded pressure vessels construction.

The weldability of the remaining steels of the group, steels 6, 7, 10 and 11, is limited for the carbon ranges indicated. Preheating is advisable and stress relieving necessary for welded structures of any magnitude.

The higher carbon types, such as Man-Ten and Jalten, by reason of their greater hardenability, are reported to possess a substantial resistance to abrasion and can be quite effectively flame hardened. Their hardenability is due to their relatively high carbon content in combination with alloying elements rather than the particular alloying elements present. Other low alloy steels with similar high carbon will also possess high hardenability with accompanying resistance to abrasion and great response to flame-hardening operations.

The original steel of this group, Steel 6, was sensitive to variation in rolling practice, brittleness due to coarse grain developing in some early important bridge sections. The vanadium and molybdenum of steels 8 and 9 tend to eliminate this sensitivity to rolling variables by their grain refining effect. The copper bearing steel, 10, is reported to possess some enhanced corrosion resistance.

Group III—Nickel and Nickel-Copper Base Steels

The three simple nickel steels are relatively old constructional steels and have been widely used. For weldability carbon is again limited. The nickel steels have superior impact resistance at sub-zero temperatures, and since 1933 possibly a hundred pressure vessels have been welded of the $2^1/_2$% nickel type for service in the low temperature dewaxing oil refining process (approximately -50°F.), in the manufacture of dry ice (-112°F.), and in the liquefaction of gases. The 2.5% nickel steel is decidedly weld hardening with carbon contents above approximately 0.18%, and with carbon contents of this approximate order stress relieving is mandatory. Less carbon can be tolerated in the 3.5% nickel steel than in the 2.5% nickel steel for welding without subsequent heat treatment.

Table 3 (Continued)

GROUP II—MEDIUM MANGANESE BASE STEELS (Manganese 1.0–1.75%)

	6	7	8	9	10	11	12		12½
	MEDIUM MANGANESE	MAN-TEN	MANGANESE VANADIUM	MANGANESE MOLYBDENUM	JALTEN	GRANITE CITY HS2	CROMANSIL		OTISCOLOY
Manufacturer	...	U. S. Steel	...	...	Jones & Laughlin	Granite City Steel Co.	...		Otis Steel Co.
Specifications (standard)	...	...	...	...	...	...	A.S.M.E. S-28		...
ANALYSIS:									
Carbon	0.30 Max.	0.35 Max.	0.13–0.18	0.10–0.20	0.35 Max.	0.20–0.30	0.25 Max.		0.12 Max.
Manganese	1.00–1.75	1.25–1.70	1.20–1.45	1.20–1.40	1.25–1.75	1.20–1.60	1.05–1.40		90–1.25
Silicon	...	0.10–0.30	0.15–0.25	0.20–0.30	0.30 Max.	0.15–0.20	0.60–0.90		0.10 Max.
Copper	*	0.25 Max.	...	0.20 Min.†	0.40 Min.	0.30 Max.	...		0.35 Max.
Vanadium	0.20 Max.†	...	0.09–0.12	...	...	...	...		...
Molybdenum	0.40 Max.†	...	...	0.20–0.30	...	...	...		...
Chromium	...	...	...	...	...	0.12	0.30–0.60		0.05 Max.
Nickel	...	...	...	...	...	...	...		0.10 Max.
Phosphorus	...	...	...	...	...	...	...		0.12 Max.
PHYSICAL PROPERTIES (AS-ROLLED):							0.09 C	0.25 C	
Yield point (1000 psi.)	50–90	55	58–71	55 Min.	50 Min.	85‡	50	67	50–70,000
Tensile strength (1000 psi.)	85–120	90	82–94	90 Min.	80 Min.	105‡	75	106	70–85,000
Elong. in 2 in., %	...	20	36–45	...	20 Min.	...	...	...	30–44
Elong. in 8 in., %	...	...	18–23	...	...	12	30	20	22–30
Izod	...	40	60–110	...	40 Min.	...	...	24	...
Charpy at 75°F., ft.-lb.	...	...	...	...	...	...	...	...	35
Charpy at −50°F., ft-lb.	...	...	...	...	...	...	...	...	15

* Copper up to 0.25% may be present.
† Optional.
‡ A certain degree of cold working may be necessary to obtain these values. Values are for wire or sheets.

Table 3 (Continued)

GROUP III—NICKEL AND NICKEL-COPPER BASE STEELS

	13 1.5% NICKEL	14 2.5% NICKEL	15 3.5% NICKEL	16 YOLOY	17 R. D. S.	18 HI-STEEL	19 H-T50
Manufacturer	...	...	...	Youngstown S. & T. Co.	Republic	Inland	Armco.
Specification (standard)	S.A.E. 2115	...	A.S.T.M. A8-39	...	...	...	...
ANALYSIS:							
					(Max.)		
Carbon	0.10–0.20	0.30 Max.	0.43 Max.	0.08–0.25	0.12 or 0.30	0.12 Max.	0.12 Max.
Manganese	0.30–0.60	0.30–0.80	0.80 Max.	...	1.00 Max.	0.50–0.70	0.15–0.90
Silicon	...	...	...	...	...	0.30 Max.	...
Nickel	1.25–1.75	2.0–2.5	3.0–4.0	2.0	0.5–1.00	0.45–0.65	0.30–0.80
Copper	*	*	*	1.0	0.5–1.50	0.90–1.25	0.30–0.80
Molybdenum	...	...	...	...	0.20	...	0.25 Max.
Phosphorus	...	...	...	...	...	0.10–0.15	0.05–0.15
PHYSICAL PROPERTIES (AS-ROLLED):							
		0.20 C 0.30 C		0.08 C 0.22 C	0.12 C 0.30 C		
Yield point (1000 psi.)	45–56	46–54 63–67	55 Min.	53–68 60–80	60 70	55–65	47
Tensile strength (1000 psi.)	63–73	75–78 99–106	90–115	70–78 88–99	75 90	78	67
Elong. in 2 in., %	30–35	... ...	...	24 27	25 18	...	...
Elong. in 8 in., %	...	27–29 18–20	19–22	25 22–26	... ...	22	28
Charpy	...	86 ...	...	43 27	... ...	40	...
Izod	...	... ...	...	... ...	75 50	...	...

* Copper up to 0.25% may be present.

Table 3 (Continued)

GROUP IV—CHROMIUM BASE STEELS
CHROMIUM-COPPER BASE STEELS
CHROMIUM-NICKEL-COPPER STEELS

	20 CHROMIUM VANADIUM		21 COR-TEN	22 CENTRALLOY		23 MAYARI R.	24 70–90	25 KONIK
Manufacturer	...		U. S. Steel	Central Steel		Bethlehem	Alan Wood	Continental Steel
Specification (standard)	S.A.E. 6120		...	...		...	...	...
ANALYSIS:								
Carbon	0.15–0.25		0.10	0.08–0.30		0.08	0.25 Max.	...
Manganese	0.50–0.80		0.10–0.30	0.60–0.90		0.50	0.75 Max.	...
Silicon	...		0.50–1.00	0.50 Max.		0.40	0.25 Max.	...
Chromium	0.80–1.10		0.50–1.50	0.25 Max.		0.50	0.25 Max.	0.30 Max.
Copper	*		0.30–0.50	0.40–0.60		0.50	0.30–0.50	0.10–0.30
Phosphorus	...		0.10–0.20	...		0.10	0.08–0.10	...
Vanadium	0.15 Min.		...	...		...	...	...
Nickel	...		...	0.25 Max.		0.35	0.25 Max.	0.20–0.50
PHYSICAL PROPERTIES (AS-ROLLED):								
	0.15 C	0.25 C		0.08 C	0.30 C			
Yield point (1000 psi.)	55	70–80	50–60	50/60	60/72	55	70 Min.	...
Tensile strength (1000 psi.)	85	104–124	65–75	65–75	75–90	75	90 Min.	...
Elong. in 2 in., %	...	...	22–27	25	20	26	20	...
Elong. in 8 in., %	20	15–18	...	...	...	..	...	...
Izod	...	...	60	...	...	...	50	...

* Copper up to 0.25% may be present.

Excellent weldability has been obtained in the low carbon varieties of steels 16 and 17 and in steels 18 and 19. In these steels additional corrosion resistance has been obtained by the addition of copper and also by the addition of phosphorus.

Group IV—Chromium Base Steels, Chromium-Copper Base Steels, Chromium-Nickel-Copper Steels

Chromium-vanadium steel, S.A.E. 6120, had been early used for forged seamless drums for high pressure service and was early suggested for welded pressure vessel construction. It is slightly weld hardening and stress relieving is mandatory.

Cor-Ten, a chromium, copper, silicon steel with phosphorus addition has apparently been designed with superior corrosion resistance rather than unusually high strength in mind. Its carbon content is low and hence its weldability excellent.

Steels 22, 23 and 24 contain relatively small percentages of a large number of alloys, copper, chromium, nickel and silicon with or without phosphorus. Their weldability is satisfactory provided the carbon content is low.

Steel 25 possesses a small percentage of chromium, nickel and copper. These small percentages have been effective in increasing the strength of cold drawn wire.

Excellent low temperature toughness characterizes certain of the copper-chrome steels.

Physical Properties (*Parent Metal*).—Table 3 also lists typical mechanical properties of the low alloy high-strength steels. These have been presented to indicate the properties being obtained with the different steels. No attempt should be made to draw comparisons of the relative merits of the different steels from these data, since they have been determined on a large number of different types of products, from heavy plates to sheets and bars, and the testing methods used have been by no means uniform.

Mechanical Properties of Welds.—The mechanical properties of welded joints in the low alloy high-strength steels depend upon many variables in welding technique, on the electrode or welding wire used and subsequent heat treatment. A large amount of data is available but is not comparative by reason of variations in types of welded samples and in testing methods. The correlation of these data has been made by the Committee on Low Alloy Steels, Welding Research Committee, The Engineering Foundation (J. H. Critchett, *Chairman*), and given elsewhere in this Chapter.

Table 5 presents mechanical properties of metal-arc weld metals obtained on a number of different low alloy high-strength steels and deposited from different electrodes. These properties have been selected, as the specimens used were of the same type (heavy plate welds). The steels chosen for presentation of weld metal physicals were not selected by reason of any greater popularity for welding purposes, and the data cannot be used in judging the superiority of any particular steel for welding. The data are presented merely to indicate typical properties of welds as used in the low alloy high-strength steels.

Table 4—Effect of Stress-Relieving Temperature on a Low-Alloy Weld Metal

All weld metal 0.505 in. diameter tension test specimens.
Time at stress-relieving temperature one hour.

		Carbon	Manganese	Silicon	Vanadium	
	Plate material	0.17	1.34	0.23	0.15	
	Electrode	0.13	1.90	0.21	0.19	
Heat Treatments	Proof Stress, psi.	Yield Point, psi.	Ultimate Tensile Strength, psi.	Elong. in 2 In., %	Reduction of Area, %	Brinell Weld Metal
As-welded		85,000	100,000	13.5	27.5	230–260
S. R. 1000°F.	85,000	86,000	98,000	18.0	42.0	197
S. R. 1150°F.	80,000	82,500	93,700	18.5	49.0	187
S. R. 1300°F.	65,000	69,500	77,000	27.0	61.0	153
S. R. 1450°F.	60,000	60,500	70,000	31.5	64.0	140
Annealed 1650°F.	47,000	52,250	65,000	33.0	66.0	134

Tensile strengths up to 100,000 psi. may be obtained in the weld metal but only at a considerable sacrifice in ductility. The relationship between tensile strength and ductility of the low alloy high-strength weld metals is presented in Fig. 7. Good average ductility is maintained up to approximately 80,000 psi. The decreased ductility characterizing weld metals of higher tensile strength would indicate that an upper limit of approximately 80,000 to 85,000 psi. should be placed on the tensile strength of the low alloy steels for use in important welded constructions. Further developments in welding may permit the production of low alloy weld metals with tensile strengths above 80,000 psi. with improved average ductility.

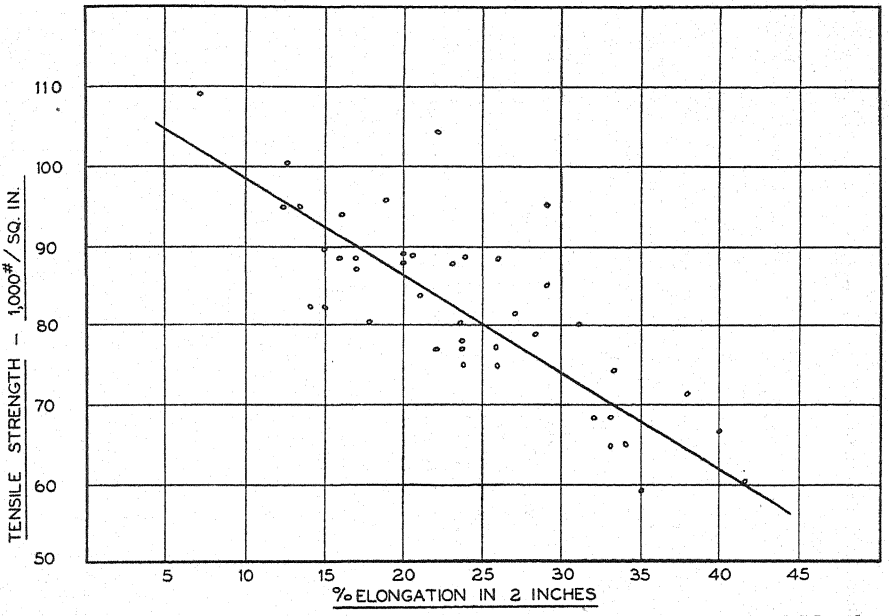


Fig. 7—Relationship of Tensile Strength to Ductility—Low Alloy Weld Metals

Properties of the affected zone of the parent metal must be considered in evaluating the mechanical properties of a welded joint. Figure 8 presents the ranges in hardness of the affected zones of a number of low alloy steels as compared with those of plain carbon steels of between 0.17 to 0.53% carbon. The hardness ranges represent the as-welded condition of the affected zones of relatively heavy plate adjacent to a single bead of metal-arc weld metal deposited at various rates of arc travel. The importance of carbon content in producing weld hardening in the low alloy steels is indicated.

The average of the hardness range of the affected zone of each steel represents what would be obtained with average arc-welding speeds of about 8 in. per minute and usual current values. The following rules as to weldability by the metal-arc processes are suggested based on experience with the welding of the various steels. They can only be considered as approximate criteria and will change dependent upon the size and rigidity of the section being welded.

Table 5—Typical Mechanical Properties of Some Low Alloy Weld Metals (Metal Arc)

Parent Metal	Electrode	Weld Metal Analysis	Heat Treatment	Tension Test 0.505-In. All Weld Metal: Y. P., 1000 psi.	T. S., 1000 psi.	Elong. in 2 In., %	Reduc. Area, %	Charpy Weld Metal
High Tensile Plate A.S.T.M. A-212	C-Mo 25%	...	S. R. 1150–1200°F. 1 hr.	57–65	72–78	20–35	40–65	...
Carbon-Molybdenum 0.25% Moly.	...	C 0.09	S. R. 1200°F. 2 hr.	41	59	35	59	37
	...	Mo 0.24						
			As-welded	58	80	24	37	...
Yoloy-0.80% Carbon	Yoloy	...	S. R. 1200°F.	70	81	27	54	...
			Ann. 1580°F.	64	77	26	53	...
			As-welded	69	95	13	12	...
Yoloy-0.20% Carbon	Yoloy	...	S. R. 1200°F.	76	91	18	20	...
			Ann. 1580°F.	69	87	17	20	...
Cromansil—1 in. thick	Cromansil	...	As-welded	98	109	7	15	10–18
T. S. 90,000 psi. C 0.23, Mn 1.12 Si 0.55, Cr 0.50	C 0.08 Mn 1.35 Si 0.18, Cr 0.43	...	S. R. 1200°F.	62	82	15	46	24–28
Cromansil—2 in. thick	Cromansil	C 0.06	S. R. 1200°F. 2 hr.	52	74	33	63	...
T. S. 80,000 psi. C 0.15, Mn 0.88 Si 0.96, Cr 0.48		Mn 1.34 Si 0.74 Cr 0.58						
	Ni-Mo	Ni 1.0 Mo 0.75 Cr 0.25	S. R. 1150°F. 1 hr.	72	88	24	..	...
	C-Mo (½%)	C 0.08 Mn 0.63 Si 0.12 Mo 0.47	S. R. 1200°F. 2 hr.	53	68	33	64	...
	Mild steel	C 0.08 Mn 0.47 Si 0.09 Cr 0.06	S. R. 1200°F. 2 hr.	49	60	41	65	...

Table 5 (Continued)

Parent Metal	Electrode	Weld Metal Analysis	Heat Treatment	Tension Test 0.505-In. All Weld Metal: Y. P., 1000 psi.	T. S., 1000 psi.	Elong., in 2 In., %	Reduc. Area, %	Charpy Weld Metal
Mn Vanadium	C 0.13 Mn 1.90 V 0.19	C 0.11 Mn 1.31 V 0.11	As-welded	85	100	13	27	...
			S. R. 1200°F. 1 hr.	83	96	19	45	28–33
	C 0.13 Mn 1.90 V 0.19	C 0.09 Mn 0.70 V 0.08	S. R. 1200°F. 1 hr.	77	87	23	55	20–24
	C 0.13 Mn 1.90 V 0.19	C 0.07 Mn 0 66 V 0.25	S. R. 1200°F. 2 hr.	47	65	34	65	38
Ni-Cr-Mo C 0.12, Mn 0.93, Si 0.23 Cr 0.67, Ni 1.63 Mo 0.30	S.A.E. 4615	...	S. R. 1150°F. 2 hr.	63	79	28	55	21–27
			Ann. 1650°F.	46	69	34	51	...
2.0–2.5% Ni C 14, Ni 2.33	2.5% Ni	...	As-welded	58	71	22	39	...
			S. R. 1200°F.	52	68	32	60	...
C 0.28, Ni 2.19	...	...	S. R. 1200°F. 2 hr.	90	94	16	33	...
			S. R. 1200°F. 12 hr.	72	83	21	44	...
			S. R. 1200°F.	59	71	30	65	...
3/5% Ni C 0.17, Ni 3.72	...	...	S. R. 1200°F. 2 hr.	77	88	21	56	...

1. If the average hardness of the affected zone of the parent metal is below 200 Brinell, the steel may be welded without preheating and without the necessity of stress relieving after welding.

2. If the average hardness of the affected zone is between 200 and 250 Brinell, slight preheating of the steel is advisable for heavier sections; stress relieving is advisable for the lighter sections and mandatory for heavier sections.

3. If the average hardness of the affected zone is above 250 or 300 Brinell, preheating to 300°F. or higher is necessary, and stress relieving necessary for both light and heavy sections.

4. If the average hardness of the affected zone is above approximately 350, preheating to 400°F. or higher is necessary, and the welded structure should not be cooled until stress relieved or annealed.

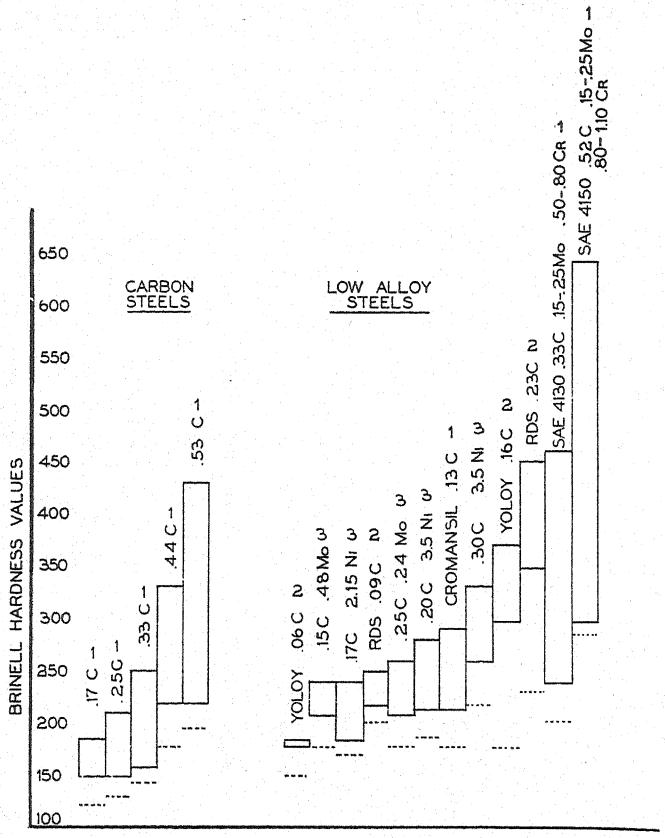


Fig. 8—Hardness of Affected Zones of Various Plain Carbon and Low Alloy Steels

(From data of Theisinger and Warner)

- - ORIGINAL PLATE HARDNESS

Area in blocks represents spread in hardness of affected zone of plate material (metal arc welds). Maximum hardness obtained with high arc travel; minimum with slowest arc travel

(1) Welding speed 4 in.–18 in. per minute
(2) Welding speed 4 in.–12 in. per minute
(3) Welding speed 6 in.–12 in. per minute

Table 6—Analyses of Carbon-Molybdenum Steels and Low Chrome-Molybdenum Steels for High Temperature Service

Steel No.	1	2	3	4	5	6	7
Name	Carbon Molybdenum 0.5%	Carbon Molybdenum 1%	Silicon Molybdenum	Chromium Molybdenum (1) (2)	Chromium Molybdenum (3) (4)	Chromium Molybdenum (1) (2)	Chromium Molybdenum (1) (2)
Specification	A.S.T.M. A206-40T	...	A158-40T Grade P15	A.S.T.M. 200-40 Grade 1 A158-40T Grade P11	A200-40 Grade 3 A158-40T Grade P3a	A200-40 Grade 4 A158-40T Grade P3b	A200-40 Grade 2
Carbon	0.10–0.20%	0.10–0.20%	0.15 Max.	0.15 Max.	0.15 Max.	0.15 Max.	0.15 Max.
Manganese	0.30–0.60	0.30–0.60	0.30 Max.	0.30–0.60	0.40–0.60	0.30–0.60	0.50 Max.
Silicon	0.10–0.50	0.25 Max.	1.15–1.65	0.50–1.00	0.45–0.75	0.50 Max.	0.50–1.00
Molybdenum	0.45–0.65	0.90–1.10	0.45–0.65	0.45–0.65	0.60–0.80	0.45–0.65	0.45–0.65
Chromium				1.00–1.50	1.50–2.00	1.75–2.25	2.25–2.75

Steel No.	8	9	10	11
Name	Chromium Molybdenum (3) (4)	4–6% Chromium	4–6% Chromium-Silicon Molybdenum(4)	4–6% Chromium-Molybdenum Stabilized with Titanium or Columbium†
Specification	A200-40 Grade 5	A158-40T Grade P5a	A158-40T Grade P5b	A158-40T Grade P5c
Carbon	0.15 Max.	0.15 or 0.20 Max.	0.15 Max.	0.10 or 0.15 Max.
Manganese	0.30–0.60	0.50 Max.	0.30 Max.	0.50 Max.
Silicon	0.50 Max.	0.50 Max.	1.00–2.00	0.50 Max.
Molybdenum	0.80–1.00	0.45–0.65*	0.45–0.65	0.45–0.65
Chromium	2.75–3.25	4.00–6.00	4.00–6.00	4.00–6.00

* Either molybdenum or 0.75 to 1.25 tungsten shall be used.

† Titanium 4 to 6 times carbon. Columbium 8 to 10 times carbon.

(1) Available with silicon within the range 1.0–1.5%.

(2) Available with silicon within the range 1.0–1.5% and with aluminum approximately 0.50–0.75%.

(3) Available with silicon within the range 1.0–1.5%. Molybdenum content is lower (0.45–0.65).

(4) Available with silicon within the range 1.0–1.5% and with aluminum approximately 0.50–0.75%. Molybdenum content is lower (0.45–0.65%).

A.S.T.M.-A206-40T—"Seamless Carbon-Molybdenum Alloy Steel Pipe for High Temperature Service."

A.S.T.M.-A158-40T—"Seamless Alloy Steel Pipe for High Temperature Service."

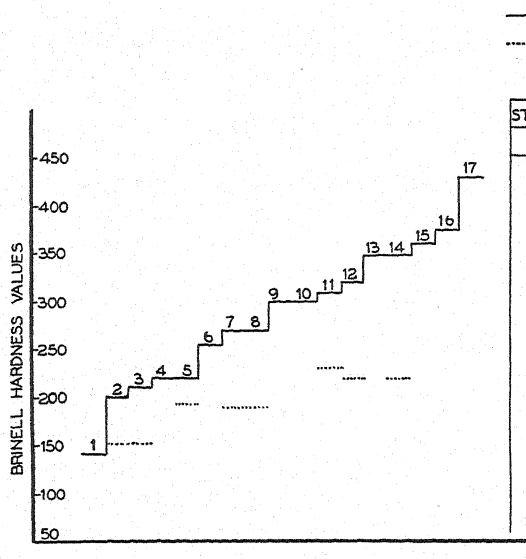
A.S.T.M.-A200-40—"Seamless Intermediate Alloy Steel Cracking Still Tubes."

Welded Design.—No special precautions are necessary on the design of low alloy high-strength steels for welded construction. For steels with very pronounced weld hardening characteristics, greater flexibility in the structure to be welded is desirable to permit ready movement to accommodate shrinkage. Successful design of the low alloy high-strength steel structures presupposes the use of tubular sections, box sections, and other sections of high ratio of section rigidity to unit weight.

LOW ALLOY STEELS FOR HIGH TEMPERATURE SERVICE

One-half Per Cent Molybdenum Steels

The $^1/_2$% molybdenum steels have excellent weldability provided the carbon content is low. No serious difficulties have been encountered



STEEL NO.	CHEMICAL ANALYSIS C	MN	SI	CR	MO	SPEC. ELEM.
1	.08	.42	.02	–	–	–
2	.15	.52	.18	–	.53	–
3	.11	.19	1.35	–	.50	–
4	.14	.40	.21	–	1.05	–
5	.10	.44	.33	1.96	.56	–
6	.17	.24	1.22	1.06	.59	AL. .57
7	.06	.45	.40	5.13	.56	TI .43
8	.09	.41	1.32	2.06	.51	–
9	.15	.42	1.37	1.30	.50	–
10	.12	.46	.35	2.34	1.00	–
11	.11	.45	.40	3.06	.95	–
12	.10	.45	.31	5.25	.48	CB. .60
13	.12	.43	1.57	3.26	.51	–
14	.10	.38	1.55	4.83	.51	–
15	.11	.35	.28	5.07	.46	–
16	.18	.30	1.27	3.10	.59	AL. .57
17	.19	.26	1.36	5.03	.51	AL. .84

Fig. 9—Relative Hardness of Affected Zone of C-Mo Steels and Low Chromium Molybdenum Steels (Metal Arc Welds Made Under Comparable Conditions)
From data obtained by the laboratories of the Babcock & Wilcox Company and the Babcock and Wilcox Tube Company)

in welding even heavy plate structures of this steel. A number of welded pressure vessels for oil refinery service and for superheater drums have been constructed to U-68 requirements (A.S.M.E. Boiler Code). Table 7 shows typical mechanical properties of $^1/_2$% molybdenum weld metal. The steel has also been used for a considerable amount of welded power plant piping for the steam lines from the boiler to the turbines. These lines generally involve cast valves of $^1/_2$% molybdenum steel but with carbon content as high as 0.30%. This higher carbon content in the $^1/_2$% molybdenum valves necessitates preheating in welding to the valve. Preheating for carbon contents in excess of 0.15% is generally recommended. the higher the carbon content the greater the preheating temperature employed.

Table 7—Mechanical Properties of ½ % Molybdenum Weld Metal (as Used in Heavy Pressure Vessel Construction)

	Yield Point, psi.	Tensile Strength, psi.	Elongation in 2 In., %	Reduction of Area, %	Hardness		
					Original Plate	Affected Zone	Weld Metal
As-welded	57,500	75,000	24.0	44.0	128	153–163	150–170
S. R. 1200°F. 2 hr.	52–63,000	68–75,000	28.0	50.0	115	135–145	130–135

Tensile specimens—0.505-in. diameter all weld metal

	Carbon	Manganese	Silicon	Molybdenum
Plate analysis	0.17	0.60	0.22	0.45–0.65
Weld analysis	0.09	0.40	0.15	0.45–0.64

Table 8—Mechanical Properties of Typical Low-Chromium-Molybdenum Fusion Welds (Metal Arc)

(Showing Effect of Heat Treatment)

Analysis of Plate	C 0.17, Cr 2.00, Mo 0.48, Mn 0.59, Si 0.30		C 0.17 Cr 1.63 Mo 0.70		C 0.13, Cr 5.0, Mo 0.50					
Weld Number	1		2	3	4					
Analysis of Weld Metal	C 0.16, Cr 1.29, Mo 0.47, Mn 0.69, Si 0.33		C 0.11 Cr 1.60 Mn 0.60	C 0.09 Cr 2.78 Mo 0.45 Si 0.12	C 0.13, Cr 4.1, Mo 0.50					
Heat treatment	As-Welded	S. R. 1300°F. 2 hr.	Ann.† 1650°F.	Ann.† 1575°F.	Ann.† 1475°F.	As-Welded*	S. R. 1200°F. 1 hr.	1300°F. 4 hr.	Ann.† 1500°F.	Ann.† 1600°F.
Yield point, 1000 psi.	...	65	48	47	42	...	106	70	45	30
Tensile strength, 1000 psi.	97.75	94.3	74.5	72.35	70	60*	117	94	78	76
Elongation in 2 in., %	Nil	21	32	32	35	Nil*	15	24	31	31
Reduction of area, %	...	38	51	57	65	...	42	55	61	58
Charpy-weld metal	7–10	18–23	26	...	...	...	...	...	...	20–35
Brinell										
Original plate	147	144	141	145	144	...	...	...	...	...
Affected zone	240–255	190–200	141	220–280	141	...	...	...	...	...
Weld metal	255–280	200–216	137–147	210–250	130	390–440	240–270	200–230	160–170	145–155

* Transverse cracks in specimen produced by cooling weld without subsequent heat treatment.
† Slowly cooled in furnace at rate of approximately 50°F. per hour to 1200°F.
Tension tests on all weld metal 0.505-in. diam. specimens.

Low Chromium Steels

The various chromium bearing steels of Table 6 are all weldable, but generally require special welding technique involving preheating for arc welding. Stress-relieving or softening treatment after welding is also generally necessary. Fortunately the steels are restricted in use to relatively light parts, such as tubing or piping, and no large welded structures have been produced to date. The construction by welding of a large pressure vessel of steels with the pronounced weld hardening characteristics of this group would be a practical impossibility.

The most widely used of this group of steels is the 4–6% chromium–$^1/_2$% molybdenum steel. Its air-hardening characteristics are pronounced, and welds from electrodes of the same analysis will crack unless preheating is used. Preheating temperature should be 300 to 400 °F. or higher. Satisfactory softening of the welded joints may be obtained by stress-relieving at 1300 °F. for a long period of time. Full softness of the weld is attained by a full anneal at 1600 °F. followed by slow furnace cooling at a rate of 50 °F. per hour until a temperature of 1200 °F. is reached. Air cooling may follow from this temperature.

Table 8 shows typical mechanical properties of four welds of variable chromium content in the weld metal.

The air-hardening characteristics of these steels may be reduced by additions of elements such as titanium or columbium. Too great an addition of these special elements will suppress the transformations of steels, thus causing brittleness due to grain growth on heating to welding temperatures. This brittleness cannot be eliminated by heat treatment since the large grained structures in transformationless steels cannot be refined by heat treatment alone. The amount of these added elements must be nicely balanced with respect to carbon content of the steel to assure both lack of air-hardening characteristics and freedom from brittleness.

All of the low chrome steels may be successfully acetylene welded without particular precautions. Flash butt welding is employed extensively in joining end to end tubes of these various steels.

CHEMICAL AND PHYSICAL PROPERTIES OF TYPICAL LOW ALLOY STEELS

There is a wide variety of low alloy steels in use for general structural and engineering purposes but information on the properties and weldability has been scattered through the literature and thus not readily available for reference purposes. Efforts have recently been made to compile and correlate the data on these steels in such form that they may be more readily compared and the factors entering into the problem of welding them, more readily brought out. The result has been a compilation of data which is presented in tables A, B, C and D. For clarity and simplicity the data have been restricted to fusion welded butt joints.

For ready reference Table A gives the type and analysis of the steels

TABLE A

ANALYSES OF TYPICAL LOW ALLOY STEELS

No.	Name	C	Mn	Si	P	Cr	Ni	Mo	V	Cu	Reference
101	Cor-Ten	0.09	0.22	0.508	0.10–0.20	0.97	...	..	..	0.38	Am. Weld. Soc. Jl., **14**, pp. 2–8, Sept. 1935, Gibson.
102	Cr-Cu-P	0.12	0.40	0.76	0.16	1.08	.	.	...	0.39	Am. Weld. Soc. Jl., **15** (Suppl.), pp. 21–32, Oct. 1936, Warner.
103	Chromephos Special Cu-Ni-P & 0.35 Cr	0.08	0.48	0.130	0.118	0.35	0.50	..	...	1.06	*A. I. M. E.*, T. P. 697, Feb. 1936, Epstein, Nead & Halley.
104	Cromansil	0.12–0.15	1.1–1.4	0.7–0.8	. .	0.4–0.6	..	..	...	..	*Iron Age*, **138**, p. 32, Dec. 31, 1936, Jennings.
105	Cu-Ni-Cr	0.07	0.42	0.224	0.010	0.69	0.45	..	...	0.80	*A. I. M. E.*, T. P. 697, Feb. 1936, Epstein, Nead & Halley.
106	Nickel	...	...	...	..	..	1.0–2.0	..	.	..	*Weld. Engr.*, **21**, pp. 22–24, July 1936, Larson.
107	Yoloy	0.08	...	...	...	..	1.99	.	..	1.02	Am. Weld. Soc. Jl., **14** pp. 2–8, Sept. 1935, Gibson.
108	R.D.S.	0.09	0.85	0.03	0.02	..	1.08	0.10	...	1.60	Am. Weld. Soc. Jl., **15** (Suppl.), pp. 21–32, Oct. 1936, Warner.
109	R.D.S.	0.095	...	...	0.04 (max.)	..	0.75	0.07	...	1.44	*Iron Age*, **138**, p. 35, Dec. 31, 1936, Jennings.
110	Cu-Ni-P	0.08	0.48	0.130	0.120	..	0.47	.	.	1.05	*A. I. M. E.*, T. P. 697, Feb. 1936, Epstein, Nead & Halley.
111	Mn-Mo (Manganese-moly.)	0.12	1.00	0.21	0.03	..	...	0.49	...	..	Am. Weld. Soc. Jl., **15** (Suppl.), pp. 21–32, Oct. 1936, Warner.
201	Cr-V	0.10–0.20	0.3–0.6	0.2–0.3	0.04	0.8–1.1	...	..	0.15–0.20	..	*Iron Age*, **139**, pp. 27–28, Jan. 14, 1937, Jennings.
202	Cr-V	0.30	...	...	...	0.8–1.10	...	..	0.15–0.20	..	*Weld. Engr.*, **21**, pp. 22–24, July 1936, Larson.
203	Nickel	0.30	...	...	...		3.0–3.8	..	...	..	*Weld. Engr.*, **21**, pp. 22–24, July 1936, Larson.
204	3½% Nickel	0.1–0.2	0.30–0.60	0.15–0.30	0.04	..	3.25–3.75	..	...	..	*Iron Age*, **138**, p. 32, Dec. 31, 1936, Jennings.

205	3½% Nickel	0.23	0.64	0.18	...	..	3.27	..	...	..	Am. Weld. Soc. Jl., **15** (Suppl.), Oct. 1936, Warner.
206	Nickel	<0.30	...	...	...	..	2.0–3.0	..	..	..	*Weld. Engr.*, **21**, pp. 22–24, July 1936, Larson.
207	2% Ni (Ni boiler plate)	0.22	0.62	0.14	...	..	2.09	..	...	..	Am. Weld. Soc. Jl., **15** (Suppl.), p. 23, Oct. 1936, Warner.
208	Yoloy	0.22	...	...	...	..	1.98	..	...	0.92	Am. Weld. Soc. Jl., **14**, pp. 2–8, Sept. 1935, Gibson.
209	R. D. S.	0.23	0.72	0.02	0.02	..	0.79	0.15	..	1.56	Am. Weld. Soc. Jl., **15** (Suppl.), pp. 21–32, Oct. 1936, Warner.
210	R. D. S.	0.2	...	...	0.04 (max.)	..	0.75	0.76	..	1.30	*Iron Age*, **138**, p. 35, Dec. 31, 1936, Jennings.
211	R. D. S.	0.23	...	...	...	..	0.75	0.16	...	1.30	Am. Weld. Soc. Jl., **14**, pp. 2–8, Sept. 1935, Gibson.
212	Manganese	<0.30	1.0–1.5	...	...	..	...	..	...	..	*Weld. Engr.*, pp. 22–24, July 1936, Larson.
213	Mn-V	0.19	1.62	0.25	0.04	..	...	..	0.17	..	*Iron Age*, **139**, pp. 28–29, Jan. 14 1937, Jennings.
214	Mn-Mo (Manganese-moly.)	0.17	1.57	0.43	0.02	..	...	0.38	...	..	Am. Weld. Soc. Jl., **15** (Suppl.), pp. 21–32, Oct. 1936, Warner.
215	Mn-V	0.15	1.29	0.20	0.04	..	...	..	0.11	..	*Industry & Welding*, **8**, pp. 52–53, Feb. 1936.
301*	Cr-Mo (S.A.E. X4130)	0.30	0.45	...	0.04 (max.)	0.9	...	0.17	...	..	*Iron Age*, **139**, p. 28, Jan. 14, 1937, Jennings.
302	3½% Nickel	0.35	0.62	0.16	...	0.22	3.27	..	...	..	Am. Weld. Soc. Jl., **15** (Suppl.), pp. 21–32, Oct. 1936, Warner.
303	Man-Ten	0.25–0.35	1.25–1.70	0.15 (min.)	0.40	..	...	..	...	..	*Iron Age*, **138**, p. 33, Dec. 31, 1936, Jennings.
304	Man-Ten	0.27	1.54	0.20	...	..	...	..	...	..	Am. Weld. Soc. Jl., **14**, pp. 2–8, Jan. 1935, Gibson.
305	Mn-Cu (Krupp 52)	0.30	1.40	0.20	...	..	...	..	...	0.25	Am. Weld. Soc. Jl., **15** (Suppl.), pp. 21–32, Oct. 1936, Warner.
306	Cu-Mo	0.29	0.74	0.24	0.03	..	...	0.22	...	0.35	Am. Weld. Soc. Jl., **15** (Suppl.), pp. 21–32, Oct. 1936, Warner.

* When welded with aircraft technique this steel falls in the 100 series.

TABLE B

PHYSICAL PROPERTIES OF THE STEELS LISTED IN TABLE A

No.	Name	Condition	Type Welding	Fracture	Y. S. M / Sq. In.	T. S. M / Sq. In.	% El. in 2 Inches	% R. A.	Charpy Impact Ft.-Lb.
101	Cor-Ten	As-rolled			51	74	41	55	
		As-welded	E	P	50	75	23***	61	
102	Cr-Cu-P (Cor-Ten)	As-rolled			44	76	59**		873 (T. I.)
		Stress relieved			46	75	59**		836 (T. I.)
		As-welded	E—C-Mo		46	85	25**		744 (T. I.)
		Stress relieved	E—C-Mo		41	78	26**		707 (T. I.)
103	Cu-Ni-P and 0.35% Cr (Chromephos Special)	As-rolled[1]			72	82	22***		28
		Norm. 1650° F.[1,2]			63	77	21***		31
		As-rolled[3]			70	80	23***	65	42
		Norm. 1650° F.[3]			63	78	23***	71	44
		As-welded[1]	E—C-Mo	W	60	80	10***		
		As-welded[1]	E—C-Mo	P	58	82	19***		
		Machined[1]	E—C-Mo	W		64	1***		
		Machined[1]	E—C-Mo	W		62	1***		
		As-welded[3]	E—C-Mo	P	69	79	21***	67	
		As-welded[3]	E—C-Mo	P	67	79	20***	65	
		Machined[3]	E—C-Mo	P	68	80	19***	61	
		Machined[3]	E—C-Mo	W	65	65	13***	21	
		As-welded	G—(Base Material)	P	69	82	21***		
		As-welded	G—(Base Material)	P	68	81	21***		
		Machined	G—(Base Material)	W	69	76	8***		
		Machined	G—(Base Material)	W		48	0***		
		As-welded	G—(Base Material)	P	66	80	19***	66	
		As-welded	G—(Base Material)	P	65	79	20***	62	
		Machined	G—(Base Material)	W	66	66	1***	7	
		Machined	G—(Base Material)	W	64	78	8***	11	
104	Cromansil	As-rolled			55–60	80–90	20–28	50–62	
		As-welded	E—Low C		45	78	24		
		Stress relieved	E—Low C		42	75	26		
		As-welded	E—Moly alloy		60	91	22		
		Stress relieved	E—Moly alloy		56	88	26		
105	Cu-Ni-Cr (Chromecop)	As-rolled[1]			65	75	24***		34
		Norm. 1650° F.[1,2]			52	68	25***		34
		As-welded	E—C-Mo	P	61	74	20***		
		As-welded	E—C-Mo	P	61	74	22***		
		Machined	E—C-Mo	W		46	0***		
		Machined	E—C-Mo	W		46	0***		
		As-welded	G—(Base Material)	P	62	75	17***		
		As-welded	G—(Base Material)	P	60	74	17***		
		Machined	G—(Base Material)	P	65	73	19***		
		Machined	G—(Base Material)	P	65	73	20***		

106	Nickel	As-rolled			40–50	60–70	40–50		
		Welded and stress relieved	E		45–55	60–75	25–35		
107	Yoloy	As-rolled			54	67	29	62	
		As-welded	E	P	57	63	29	70	
		As-welded	E	P	65	69	26	66	
		Stress relieved	E	P	80	83	24	57	
		Stress relieved	E	W	72	84	20	37	
		Stress relieved	E	P	57	71	29	64	
		Stress relieved[4]	E	P	70	73	29	64	
		Stress relieved	E	P	55	68	35	62	
		Stress relieved	E	P	53	68	33	60	
		As-welded	E	P	86	95	27	42	
		As-welded	E	P	85	92	27	44	
108	R. D. S.	As-rolled			41	87	47**		740 (T. I.)
		Stress relieved			50	73	55**		706 (T. I.)
		As-welded	E—C-Mo		44	86	33**		688 (T. I.)
109	R. D. S.	As-rolled			68	82	33	54	
		As-welded	E—C-Mo*		70	85	29		
110	Cu-Ni-P (HI Steel)	As-rolled[1]			73	80	23***		28
		Norm. 1650° F.[1,2]			62	75	21***		29
		As-rolled[3]			69	77	22***		42
		Norm. 1650° F.[1,3]			63	75	25***		46
		As-welded	E—C-Mo	W	70	78	10***		
		As-welded	E—C-Mo	P	69	80	18***		
		Machined	E—C-Mo	W		59	0***		
		Machined	E—C-Mo	W		74	1***		
		As-welded	E—C-Mo	P	67	77	20***	66	
		As-welded	E—C-Mo	P	67	78	20***	65	
		Machined	E—C-Mo	P	66	76	12***	41	
		Machined	E—C-Mo	W	65	78	2***	27	
		As-welded	G—(Base Material)	P	68	79	15***		
		As-welded	G—(Base Material)	P	69	80	16***		
		Machined	G—(Base Material)	W	67	75	7***		
		Machined	G—(Base Material)	W	67	67	3***		
		As-welded	G—(Base Material)	P	65	78	21***	63	
		As-welded	G—(Base Material)	P	65	78	21***	62	
		Machined	G—(Base Material)	P	65	73	17***	48	
		Machined	G—(Base Material)	W	66	74	9***	20	
111	Mn-Mo (Manganese-moly.)	As-rolled			37	84	54**		780 (T. I.)
		Stress relieved			37	80	51**		800 (T. I.)
		As-welded	E—C-Mo		52	86	30**		712 (T. I.)
		Stress relieved	E—C-Mo		50	84	38**		788 (T. I.)

TABLE B (*Continued*)

No.	Name	Condition	Type Welding	Fracture	Y. S. M / Sq. In.	T. S. M / Sq. In.	% El. in 2 Inches	% R. A.	Charpy Impact Ft.-Lb.
201	Cr-V (SAE—6115)	As-rolled			60–70	80–90	25–35		
		As-welded	E—C-Mo*		65	90	22	46	
202	Cr-V	As-rolled			55–65	85–95	25–35		
		Welded and stress relieved	E		65–80	85–100	15–20		
203	Nickel	As-rolled			45–60	70–80	30–40		
		Welded and stress relieved	E		50–65	70–85	20–30		
204	3½% Nickel	As-rolled			55–60	80–90	20–25	50–55	
		As-welded	E—Low C bare*[14]		40–45	60–70	8–10	5–10	
		As-welded	E—Low C coated*[14]		40–45	75–80	10–15	20–25	
		As-welded	E—3½% Ni coated*[14]		45–55	90–95	15–20	18–25	
		As-welded	E—2% Ni coated*[14]		40–45	80–85	15–20	20–25	
		As-welded	E—Ni-Moly*[14]		45–50	80–85	15–20	20–25	
205	3½% Nickel	As-rolled			50	90	40**		750 (T. I.)
		Stress relieved			57	84	50**		769 (T. I.)
		As-welded	E—C-Ni-Mo		55	95	17**		600 (T. I.)
206	Nickel	As-rolled			45–60	80–100	25–35		
		Welded and stress relieved	E		65–80	85–100	15–20		
207	2% Ni (Ni boiler plate)	As-rolled			42	80	50**		790 (T. I.)
		Stress relieved			50	75	60**		830 (T. I.)
		As-welded	E—C-Ni-Mo		50	85	23**		670 (T. I.)
208	Yoloy	As-rolled			64	95	26	57	
		As-welded	E	P	86	95	27	42	
		As-welded	E	P	85	92	27	44	
		Stress relieved[11]	E	W	83	90	9	17	
		Stress relieved[11]	E	W	79	101	19	33	
		Stress relieved[12]	E	W	69	88	17	24	
		Stress relieved[13]	E	W	64	81	18	38	
		Stress relieved[13]	E	W	65	80	14	16	
209	R. D. S.	As-rolled			58	105	40**		773 (T. I.)
		Stress relieved			60	89	48**		778 (T. I.)
		As-welded	E—C-Mo		53	99	22**		581 (T. I.)
210	R. D. S.	As-welded[7]	E—C-Mo		81	96	29		
		Stress relieved	E—C-Mo		94	104	22		
211	R. D. S.	As-rolled			70	90	18		
		As-welded	E—Mo coated		81	96	[9]	29	
		Stress relieved	E—Mo coated		94	105	[10]	29	

212	Manganese	As-rolled			40–60	60–90	25–35		
		Welded and stress relieved	E		50–75	65–95	15–30		
213	Mn-V	As-rolled			70–80	100–110	20–30	40–50	
		As-welded[8]	E—C-Mo		66	95	22	35	
214	Mn-Mo (Manganese-moly.)	As-rolled			36	104	42**		890 (T. I.)
		Stress relieved			47	92	46**		800 (T. I.)
		As-welded	E—C-Mo		56	95	22**		614 (T. I.)
		Stress relieved	E—C-Mo			93	37**		204 (T. I.)
215	Mn-V	As-welded	E—Mn-V	P	68	88	18	39	
		Stress relieved	E—Mn-V	P	67	87	21	51	
301	Cr-Mo (SAE X4130)	As-rolled			60–70	100–110	20–30	50–60	
		As-welded	E—C-Mo*		60	80	28		
		Stress relieved	E—C-Mo*		55	75	34		
302	3½% Nickel	As-rolled			55	107	35**		810 (T. I.)
		Stress relieved			61	100	40**		820 (T. I.)
		As-welded	E—C-Ni-Mo		55	104	21**		560 (T. I.)
303	Man-Ten	As-rolled			55–65	80–90	25–30	40–50	
		As-welded	E—Mo alloy[6]		53	90	15[4]		
		Stress relieved	E—Mo alloy[6]		51	88	20[5]		
304	Man-Ten	As-rolled			56	92	20***	47	
		As-welded	E	2 in W—1 in P	55	88	15	58	
305	Mn-Cu (Krupp 52)	As-rolled			45	91	53**		934 (T. I.)
		Stress relieved			40	80	58**		861 (T. I.)
		As-welded	E—C-Mo		50	97	27**		726 (T. I.)
		Stress relieved	E—C-Mo		35	87	36**		641 (T. I.)
306	Cu-Mo	As-rolled			45	90	40**		810 (T. I.)
		Stress relieved			50	88	42**		820 (T. I.)
		As-welded	E—C-Mo		51	93	37**		697 (T. I.)
		Stress relieved	E—C-Mo		47	87	39**		754 (T. I.)

[1] Gage 0.062 inch
[2] Air cooled.
[3] Gage 0.125 inch.
[4] 32% free bend.
[5] 40% free bend.
[6] Preheating recommended for heavy sections.
[7] For best weldability C content should be low. For higher C content preheating recommended. Heat treatment after welding recommended.
[8] Preheating beneficial for heavy sections.
[9] Bend 149%.
[10] Bend 127%.
[11] 950° F., 1 hr.
[12] 1200° F., 1 hr.
[13] 1650° F., 1 hr.
[14] Heat treatment after welding recommended.
* Preheating recommended.
** Elong. in 1 inch.
*** Elong. in 8 inches.
E—Electric
G—Gas
T. I.—Tensile Impact
C—Carbon
P—In plate
W—In weld

in question together with the source of the information as subsequently reported in Table B. In Table B those physical properties pertinent to the weldability are listed together with the type of welding involved. In addition, the steels are listed with a serial number, starting at 100, 200 and 300, respectively. An attempt has been made to list in the 100 series those steels which may be designated as foolproof from the welding standpoint. In general, these steels contain less than 0.15% carbon. In the 200 series are listed those steels which are moderately air hardening under average welding conditions. Attention must be given to the ductility of the zone adjacent to the weld in these steels. When butt welded they may or may not require a stress-relieving or tempering treatment, and when fillet welded will generally develop a very narrow zone of reduced ductility. This ductility may or may not be sufficient, depending upon the character of the structure involved. In general, these steels contain less than 0.30% carbon, but may contain slightly more, depending on the alloying constituents. In the 300 series are listed those steels in which the zone next to the weld undergoes sufficient loss of ductility to become serious from the engineering standpoint. Such steels definitely require stress relieving, unless very special conditions are involved. They generally contain 0.30% carbon or more, but may contain slightly less, depending on the alloying constituents.

Obviously, any grouping of steels on a broad basis such as the above will fail to take into account certain special conditions and special cases. For example, the chromium-molybdenum S.A.E. X4130 steel is listed in the 300 series, and it is obviously true that welded plate of this analysis must be stress-relieved. However, by contrast aircraft tubing of this analysis is free from the difficulty in question because in proportion to the thickness of the material a large amount of heat is used in the welding operation, and the hardening tendency, therefore, inhibited to a marked degree. This, however, carries with it a well-developed and somewhat special technique and may be regarded as the exception that proves the rule.

It will be noted that the information in Tables A and B results from a study of the literature. Subsequent to this study a questionnaire was sent to the leading producers and users of low alloy steels. Further information more recent in character than that in Tables A and B was obtained from that questionnaire, and this information is compiled in Tables C and D.

Naturally, there is divergence in the ideas of the various testing engineers as to the methods of testing the welded joints and reporting the results. In many instances it has been necessary to select data from the information obtained with a view to brevity and conformity. For example, the information obtained from one source was in the form of percentage deviation charts and mean values were selected from these charts for the figures given in Tables C and D. Again, hardness measurements have been reported as Vickers, Brinell or Rockwell. In the interest of conformity and for purposes of comparison these all have been converted to Rockwell *B*. In view of the fact that the original sources are designated in every case, those interested in more precise information than obtainable from the conversion figures may study the data from the original sources.

TABLE C

ANALYSES OF TYPICAL LOW ALLOY STEELS

No.	Name	C	Mn	Si	S	P	Cr	Ni	Cu	Mo	V	Source
101X	Cor-Ten	0.09	0.30	0.65	0.04	0.13	0.95	..	0.40	..	..	Carnegie-Illinois Steel Corp.
(*a*)	Cor-Ten	0.10	0.27	0.48	...	0.140	0.89	..	0.43	..	..	U. C. & C. Res. Labs.
(*b*)	Cor-Ten	0.09	0.25	0.49	...	0.140	0.89	..	0.41	..	..	U. C. & C. Res. Labs.
(*c*)	Cor-Ten	0.09	0.37	0.73	...	0.117	0.89	..	0.43	..	..	U. C. & C. Res. Labs.
104X	Cromansil	0.13	1.32	0.78	...	...	0.43	..	0.13	..	..	U. C. & C. Res. Labs.
105X	Mayari R	0.08	0.72	0.40	0.042	0.10	0.56	0.33	0.62	..	..	Bethlehem Steel Company
(*a*)	Mayari R	0.08	0.72	0.40	0.042	0.10	0.56	0.33	0.62	..	..	Bethlehem Steel Company
(*b*)	Mayari R	0.08	0.50	0.10	0.035	0.099	0.25	0.34	0.50	..	..	Bethlehem Steel Company
107X	Yoloy	0.07	0.38	...	...	...	..	1.79	0.92	..	..	A. O. Smith Corporation
(*a*)	Yoloy	0.06	0.35	0.005	...	...	..	1.73	0.93	..	..	Am. Weld. Soc. Jl., 15 (Suppl.), pp. 21–32, Oct. 1936, Warner
(*b*)	Yoloy	0.04	0.36	0.01	...	...	..	1.76	0.91	..	..	U. C. & C. Res. Labs.
(*c*)	Yoloy (max. percentages)	0.10	0.50	0.30	0.05	0.04	..	2.00	1.00	..	..	Youngstown Sheet & Tube Co.
108X	R. D. S.	0.07	0.84	...	...	...	..	0.97	1.45	0.10	..	U. C. & C. Res. Labs.
110X	Hy Steel	0.10	0.61	0.19	0.017	0.102	..	0.62	1.15	..	..	U. C. & C. Res. Labs.
112X	"AW"-70–90	0.15	0.60	Tr	0.03	0.09	..	..	0.42	..	..	Alan Wood Steel Company
206X	Nickel	0.19–0.30	0.56–1.03	0.14–0.28	...	...	..	2.08–3.61	..	..	..	Cooperative Com. on Special Steels for Ship Construction.
208X	Yoloy	0.16	0.60	0.20	...	...	..	2.09	1.06	..	..	Am. Weld. Soc. Jl., 15 (Suppl.), p. 21, Oct. 1936, Warner
212X	High Tens. Mn	0.14–0.29	1.36–1.64	0.04–0.18	...	...	..	..	..	..	..	Cooperative Com. on Special Steels for Ship Construction
(*a*)	Man-Ten	0.25	1.50	...	0.04	0.04	..	..	0.22	..	..	Carnegie-Illinois Steel Corp.
214X	Mn-Mo	0.15–0.22	0.88–1.59	0.09–0.44	...	...	..	..	..	0.22–0.34	..	Cooperative Com. on Special Steels for Ship Construction
215X	Mn-V	0.14–0.20	1.32–1.57	0.02–0.24	...	...	..	..	..	..	0.10–0.18	Cooperative Com. on Special Steels for Ship Construction
216X	Sil-Ten	0.36	0.76	0.26	...	...	..	..	0.03	..	..	Am. Weld. Soc. Jl., 15 (Suppl.), p. 21, Oct. 1936, Warner
217X	Cromansil	0.18–0.23	1.10–1.40	0.65–0.85	...	...	0.40–0.60	..	..	..	..	Cooperative Com. on Special Steels for Ship Construction

It is significant that the foolproof welding steels listed under the 100 series almost regardless of the method of welding never show a Rockwell *B* hardness of more than 96 either in the weld proper or in the metal adjacent to the weld. This hardness corresponds to approximately 200 Brinell. The steels in the 200 and 300 series when welded without special precautions invariably show a hardness greater than this amount. This leads to a very simple but dangerous method of classifying the low alloy steels from the standpoint of weldability. The method is simple in that all that is required is a hardness exploration across the joint. It is dangerous because hardness does not necessarily mean lack of ductility, and the conclusions as to the weldability should be based on ductility and not on hardness. In fact, the major initial purpose of the low alloy steels is to obtain strength or hardness, without corresponding loss of ductility.

Consider carbon steel with 0.22% carbon, gas-welded, in $^3/_4$-in. plate. This attains a Rockwell *B* hardness of 82 immediately adjacent to the weld, and this hardness is accompanied by a drop in impact strength to approximately 8 ft-lb. whereas the low alloy steels with a Rockwell *B* hardness of approximately 82 adjacent to a gas weld show an impact strength from 22 to 30 ft-lb. and substantially retain this impact strength as the hardness approaches 96. To further illustrate this point, the average value for plain 0.15% carbon steel in the as-rolled condition has been quoted as Rockwell *B* 75, with 32% elongation and 65% reduction of area. The same source quotes chromium-vanadium steel with 0.15% carbon as Rockwell *B* 86, with 30% elongation and 68% reduction of area. In other words, these steels have substantially the same ductility usually measured on tensile test, but the alloy steel shows an increase in Rockwell hardness from 75 to 86. Again, if heat treated to Rockwell *B* hardness of 94 the plain 0.15% carbon steels are quoted at 20% elongation and 50% reduction of area, whereas the chromium-vanadium 0.15% carbon steels heat treated to the same hardness, *B* 94, show 30% elongation and 62% reduction of area. Obviously, hardness is no more than a very rough qualitative index of ductility and may be highly misleading.

Those who have not devoted themselves to this special field of activity may wonder that a report on weldability of low alloy steels makes little mention of welding technique. In effect, such mention would be redundant because within the range of analyses now available and covered in this report the welding technique does not differ from that used in the welding of plain carbon steel in any respect, with the possible exception that the welding rod or electrode may contain small amounts of alloys. This is true because the amount of alloying elements is so low as to have little or no effect on the fluidity of the metal proper or on the nature of the slag formed during the welding operation.

No attempt has been made to draw conclusions from the data here presented, except as such conclusions may be implied by the grouping. The grouping is, however, designated for the general case and may not apply where specific welding conditions and specific welding techniques are involved, and like all generalizations should be used with caution. It is the thought of the Committee that the data should speak for themselves and confirm the host of applications of the welded low alloy steels based on sound engineering judgment.

TABLE D

Physical Properties of the Steels Listed in Table C

No.	Name	Condition	Type Welding	Fracture	Y.S. M Lb./ Sq. In.	T.S. M Lb./ Sq. In.	% Elong. in 2 Inches	% R. A.	Charpy Impact Ft.-Lb.	Max. Loc. Hardness Over 96 Rock. B
101X	Cor-Ten	As-rolled			50	70	21		40	
(*a*)	Cor-Ten	As-rolled			48	72	46	68		
		As-welded	G—bare	P	44	73	32		23	No
		Stress relieved[1]	G—bare	P	47	72	33		33	No
(*b*)	Cor-Ten	As-rolled			57	74	41	66		
		As-welded	G—bare	P	52	73	25			No
		Stress relieved[1]	G—bare	P	52	73	33			
(*c*)	Cor-Ten	As-rolled			50	77	33	57		
		As-welded	G—bare	P	51	76	24			No
		Stress relieved[1]	G—bare	P	51	72	25			
104X	Cromansil	As-rolled			60	82	43		28 (I.)	
		As-welded	G—bare	P	59	86	17		31 (I.)	No
105X	Mayari R	As-rolled			66	82	28	65		
		As-welded	E—M.S. coated	P	71	83	21	42		No
		Stress relieved[2]	E—M.S. coated	W	62	75	23	50		
										No
105X	Mayari R	As-rolled			55	78	26	61	80 (I)	
(*a*)		As-welded	E—M.S. coated	W	65	82	10	17		No
		Stress relieved[3]	E—M.S. coated	P	59	80	20	35		No
(*b*)	Mayari R	As-rolled			52	69	30	61		
		As-welded	E—M.S. coated	P	56	70	23	47		No
		Stress relieved[3]		P	52	66	25	59		No
107X	Yoloy	As-welded	Yoloy coated rod		66	80	21			
(*a*)	Yoloy	As-rolled			48	71	56**		769 (T. I.)	
		Stress relieved			45	68	61**		730 (T. I.)	
		As-welded	E—C-Mo coated	P	47	74	16**		788 (T. I.)	No
		Stress relieved	E—C-Mo coated	P	40	74	17**		651 (T. I.)	No
(*b*)	Yoloy	As-rolled			48	61	30	71	42 (I.)	No
		As-welded	G—bare	P	45	62	30			No
		Stress relieved[1]	G—bare	P	63	76	31			
(*c*)	Yoloy (high ductility)	As-rolled			50–55	67–76	29–26*		43	
		Transverse			50–55	67–76	26–23*			
		Weld spec. as-welded	E—Yoloy or C coated		71	80	23	33		
		Weld spec. stress relieved[4]	E—Yoloy or C coated		68	79	28	54		
		Joint as-welded	E—Yoloy or C coated	P	58	76	21	55	30	No
		Joint stress relieved[4]	E—Yoloy or C coated	P	55	72			W 25 B 55	No

TABLE D (*Continued*)

No.	Name	Condition	Type Welding	Fracture	Y.S. M Lb./ Sq. In.	T.S. M Lb./ Sq. In.	% Elong. in 2 Inches	% R.A.	Charpy Impact Ft.-Lb.	Max. Loc. Hardness Over 96 Rock. B
108X	R. D. S.	As-rolled			62	83	25	56	27 (I.)	
		As-welded	G—bare	P	60	97	13			No
		Stress relieved[1]	G—bare	P	61	83	19			
110X	Hy steel	As-rolled			65	77	33	68		
		As-welded	G—bare	P	56	76	27			No
		Stress relieved	G—bare	P	58	76	21			
112X	"AW"-70-90	Normalized			55–65	70–80	25	55	65	
		Annealed			45–50	62–70	25–28	55–60		
		Stress relieved			50–60	65–75	25	55		
		Transv. Norm.			55–65	70–80	25	55	65	
		As-welded[5]	E—bare C	P	54	75	28	62		No
		As-welded[6]	E—bare C	P	63	78	28			
		As-welded[7]	E—bare C	W	63	75	17			
		As-welded[8]	E—bare C	P	62	71	25			
		As-welded[8]	G—1/16 H.T	P	53	68	13			
		As-welded[8]	G— 3 Ni	P	55	73	16			
		As-welded[5]	G—1/8 H.T.	W	59	62	5			
		As-welded[5]	G—1/8 H.T. (backhand)	P	54	67	18			
206X	Nickel	As-rolled			55 (Min.)	88 (Min.)	15* (Min.)			
			E—Fl. 5				9	11	26	
			E—Fl. 5				8	18	36	
			E—Fl. 5				12	26	38	
			E—Fl. 85				23	32	25	
			E—Var.				10	20	23	
			E—G.E.				12	21	25	
208X	Yoloy	As-rolled			54	87	50**		812 (T. I.)	
		Stress relieved			56	81	52**		797 (T. I.)	
		As-welded	E—C-Mo coated	P	48	84	22**		435 (T. I.)	Yes
		Stress relieved	E—C-Mo coated	P	52	85	22**		727 (T. I.)	
212X	High Tens. Mn	As-rolled			55 (Min.)	88 (Min.)	15* (Min.)			
			E—Fl. 5				9	15	32	
			E—Fl. 5				7	15	36	
			E—Fl. 5				12	23	33	
			E—Fl. 85				10	14	33	
			E—Var.				12	23	21	
			E—M-C Mo				9	16	27	
			E—Wilson 9				7	12	24	

212X	Man-Ten	As-rolled		50	80	19		40 (I.)	
(a)		As-welded	E—M.S. coated	55	88	15*			Yes
214X	Mn-Mo	As-rolled		(Min.)	(Min.)	(Min.)			
			E—Fl. 5			11	25	32	
			E—Fl. 5			9	21	31	
			E—Fl. 5			12	34	33	
			E—Fl. 85			13	19	30	
			E—Var.			13	24	21	
			E—M-C			11	21	20	
			E—M-C Mo			12	25	27	
			E—G.E.			10	19	29	
215X	Mn-V		E—Fl. 5			17	28	31	
			E—Fl. 5			11	21	33	
			E—Fl. 5			14	32	35	
			E—Fl. 85			23	42	27	
			E—Var.			13	22	27	
			E—M-C			11	18	27	
			E—M-C Mo			34	44	24	
216X	Sil-Ten	As-rolled		36	96	43**		895 (T. I.)	
		Stress relieved		36	89	46**		875 (T. I.)	
		As-welded	E—C-Mo coated	48	97	23**		698 (T. I.)	Yes
		Stress relieved	E—C-Mo coated	44	92	36**		745 (T. I.)	
217X	Cromansil	As-rolled		55	88	15*			
				(Min.)	(Min.)	(Min.)			
			E—Fl. 5			11	21	33	
			E—Fl. 5			9	18	32	
			E—Fl. 5			14	37	35	
			E—Fl. 85			31	44	28	
			E—Var.			10	16	30	
			E—M-C			9	20	29	
			E—M-C Mo			8	16	27	

[1] 1200° F., 1 hr.
[2] 1475° F.
[3] 1050° F.
[4] 1 to 1½ hr. at 1150–1200° F.
[5] 3/16
[6] 12 Gage
[7] 13 Gage
[8] 16 Gage
Fl.—Fleetweld
Var.—Various
M. S.—Mild Steel
M-C—Murex-Cresta
G. E.—General Electric
B—Foundry
E—Electric
G—Gas
I—Izod
T. I.—Tensile Impact
C—Carbon
P—In plate
W—In weld
* El. in 8″
** El. in 1″

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CHAPTER 19

CHROME IRONS AND STEELS*

Classification of Chromium Irons and Steels, Metallurgical and Physical Properties, Welding Procedure—Filler Metal, Welding Processes, Welding Dissimilar Metals, Testing.

CLASSIFICATION OF CHROMIUM IRONS AND STEELS

THE scope of this chapter is limited to the chromium irons and steels containing from 3 to 30% chromium. Steels containing less than 3% chromium are classified as low alloy steels and they are of sufficient importance to be included in a separate chapter on the low alloy group. Straight chromium steels containing more than 30% chromium are not covered because they are yet to attain commercial importance. The "straight" chromium steels include the alloys of iron-chromium and carbon with their modifications, and are to be distinguished from the chromium steels which contain nickel in sufficient quantities to materially alter their properties.

The American Iron & Steel Institute has classified the chromium irons and steels, and the commercial types are as follows:

Type No.	Carbon	Chrome	
403	0.12 Max.	11.50–13.00	
405	0.08 Max.	11.50–13.50	Aluminum, 0.10–0.20
406	0.12 Max.	12.00–14.00	
410	0.12 Max.	10.00–14.00	
418	0.12 Max.	12.00–14.00	Tungsten, 2.50–3.50
430	0.12 Max.	14.00–18.00	
438	0.12 Max.	16.00–18.00	Tungsten, 2.50–3.50
442	0.35 Max.	18.00–23.00	
446	0.35 Max.	23.00–30.00	
502	0.10 Max.	4.00– 6.00	

Note: The free machining and cutlery steels are not included in the above table.

The name "chromium iron" has been applied by the industry to distinguish the non-hardening types from the cutlery and other hardening types which are called steels, but since there is no accepted division line, the single term "steel" will be used throughout this chapter.

These steels may be classified in accordance with their weldability by dividing them into two general groups, the hardening and the non-hardening alloys, which, in metallurgical terms, are called the martensitic and

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ferritic steels, respectively. Between these two classes, there is a zone from 14 to 18% chromium within which the hardenability decreases as the chromium increases with a given carbon content. Below 14% chromium, the chromium steels are martensitic, and above 18% they are predominantly ferritic when the carbon is within commercial ranges. The intermediate range is classed as partly martensitic and partly ferritic, the proportion for any per cent of chromium depending largely on the carbon content.

Table 1

Properties of the Principal Cr-Fe Alloys

	2% Cr	5% Cr		9% Cr	12% Cr		Cutlery		17% Cr		27% Cr	
Chemical composition												
Chromium	1.75 to 2.25	4 to 6		8 to 10	12 to 14		13 to 14		16 to 18		25 to 30	
Nickel	(0.5 Mo)	—		(1.5 Mo)	—		—		—		—	
Si and Mn (max.)	0.50	0.50		0.50	0.50		0.55		0.50		0.50	
Carbon	0.15 max.	0.10 to 0.20		0.15 max.	0.10 max.		0.30 to 0.40		0.10±		0.10±	
Specific gravity												
Lb. per cu. in.	—	0.280		0.282	0.276		0.278		0.273		0.270	
(Mild steel = 1.00)	—	0.99		1.00	0.97		0.98		0.96		0.95	
Electrical resistance												
Microhms per cm³	—	—		—	57		60		59		67	
(Mild steel = 1.00)	—	—		—	5.2		5.5		5.4		6.1	
Melting range, °F.												
Top	—	2800		—	2790		2750		2750		2750	
Bottom	—	2760		—	2250		2580		2710		2710	
Structure	Pearlitic	Pearlitic		Martensitic	Martensitic		Martensitic		Ferritic		Ferritic	
Magnetism												
Ferromagnetic	Yes	Yes		—	Yes		Yes		Yes		Yes	
Permeability (As annealed	—	—		—	—		—		—		—	
Permeability (Cold worked 10%	—	—		—	—		—		—		—	
Specific heat												
Cg.s. units, 0 to 100°C.	—	0.11		—	0.11		0.117		0.11		0.11	
(Mild steel = 1.00)	—	1.0		—	1.0		1.1		1.0		1.0	
Thermal conductivity												
*Cg.s. units at 100°C.	—	0.0874		—	0.0595		0.05		0.0583		0.0500	
(Mild steel = 1.00)	—	0.73		—	0.50		0.42		0.49		0.42	
Cg.s. units at 500°C.	—	0.0803		—	0.0686		—		0.0624		0.0583	
Thermal expansion per °F. x 1,000,000												
From 32 to 212°F.	—	6.1		6.29	6.1		5.7		6.0		5.9	
(Mild steel = 1.00)	—	0.93		0.95	0.93		0.87		0.91		0.90	
From 32 to 932°F.	—	7.2		7.00	6.7		6.6		6.7		6.3	
Mechanical Properties at Room Temperature	Annealed	Annealed	†Heat Treated	Annealed	Annealed	†Heat Treated	Annealed	††Heat Treated	Annealed	Cold Worked (Wire)	Annealed	Cold Worked (Wire)
Ultimate strength, 1000 psi.	60 to 70	66	115	75 to 87	65	125	100	230 to 260	75	100 to 190	75 to 95	85 to 175
Yield point, 1000 psi.	30 to 45	27	103	35 to 45	35	100	65	200 to 220	40	—	50 to 60	55 to 155
Elastic modulus, 10⁶ psi.	—	—	—	—	28	—	—	—	29	—	—	—
Elongation, % in 2 in.	40 to 30	38	20	40 to 30	35	20	27	8 to 2	27	—	30 to 20	—
in 10 in.	—	—	—	—	—	—	—	—	—	25 to 2	—	25 to 2
Reduction of area, %	—	76	66	—	65	60	59	20 to 2	55	40 to 20	60 to 50	55 to 25
Impact, ft-lb., Charpy	35 to 65	—	—	35 to 60	—	75	—	—	—	—	—	—
Izod	—	80	75	—	80	—	—	—	8 to 25	—	—	—
Fatigue endurance limit, 1000 psi.	—	—	—	—	—	—	—	—	—	—	—	—
Hardness, Brinell	130 to 160	136	250	145 to 190	140	230	170	480	175	185 to 270	160 to 190	150 to 250
Rockwell	—	B-75	C-24	—	B-96	C-22	—	C-56	B-85	B-90 to 105	B-80 to 90	C-0 to 25
Erichsen value, mm.	—	—	—	—	—	—	—	—	7 to 9	—	—	—
Stress in psi. causing 1% "creep" in 10,000 hr. at 1000°F.	11,400	9,000		11,600	13,000				8,500		—	
1100	5,650	—		6,950	—				—		—	
1200	3,150	—		2,300	2,300				2,100		1,600	
1350	—	—		—	1,400				1,200		400	
Scaling temp., °F.		1200		1200	1300		1750		1550		2100	
Initial forging temp., °F.		2100		—	2100		2000		2000		2800	
Finishing temp., °F.		About 1400		—	max. 1450		1700		max. 1400		max. 1400 to 1450	
Annealing treatment		Furnace cool from 1580°F.		—	Prolonged heating at 1250 to 1350°F.		1575 to 1625°F.		**		1 hr. or more at 1450°F. and quench	

* Thermal conductivity is measured as calories per sq.cm. per sec. per °C. per cm.
† Quenched and drawn at 1100°F. †† Oil Quenched from 1850°F. and drawn.
** Small cold reduction, followed by anneal at 1400°F. and quench

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Classifications of the chromium steels in accordance with their use is difficult. In general, they are all utilized for resistance to oxidation and corrosion, the range of chromium chosen for a specific application depending upon the temperature of operation and corrosive environment. Resistance to oxidation increases with the percentage of chromium (see Fig. 1), and the same is generally true for resistance to corrosion (see Table 2). Steels containing chromium in amounts over 11% have the popular name "Stainless" steels, this being the lower limit at which they resist, indefinitely, atmospheric corrosion at room temperature.

Steels containing chromium from 3 to 14%, generally modified up to 10% by the addition of molybdenum, have a wide field of use where strength and relatively mild corrosion resistance are required at elevated temperatures. The oil refining industry has used considerable tonnage for this purpose.

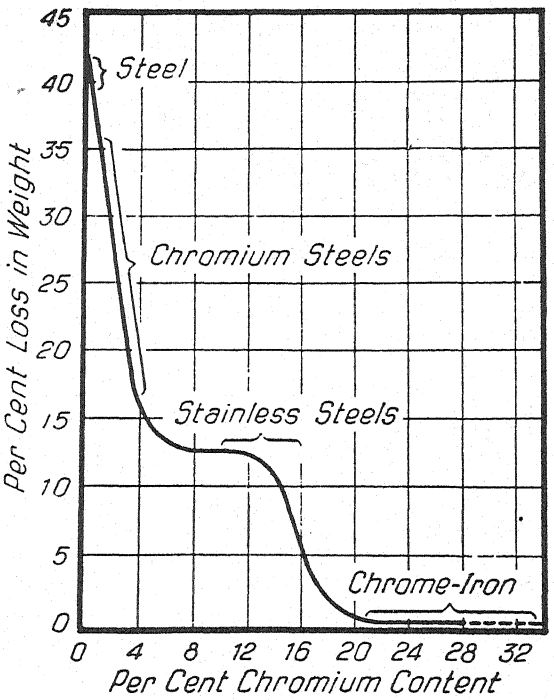


Fig. 1—Loss of Weight in 1/2-In. Cubes by Oxidation at 1000°C. for 48 Hr. (C. E. MacQuigg)

Steels containing chromium from 15 to 18% have been extensively used for corrosion resistance to nitric acid, in addition to their general use for many other purposes.

Steels containing chromium above 18% have been used mostly for service requiring maximum oxidation resistance at elevated temperatures.

Molybdenum in amounts less than 1% is generally added to the steels

Table 2—Corrosion Tests of Chromium Irons in Nitric Acid

Material	Analysis					Heat Treatment	Average Penetration In. Per Month
	Cr	C	Mn	Si	Ni		
1/2-in. plate	17.2	0.08	0.44	0.37	0.15	1425° furnace cool	0.00192
1/2-in. weld and plate	17.1	0.10	0.48	0.45	0.08	1425° furnace cool	0.00198
1/2-in. weld and plate	17.1	0.10	0.48	0.45	0.08	1425° water quenched	0.00209
5/8-in. plate	15.3	0.09	0.42	0.47	0.06	1425° furnace cool	0.00409
5/8-in. weld and plate	15.5	0.08	0.48	0.41	0.10	1425° furnace cool	0.00395
5/8-in. plate	15.3	0.09	0.42	0.47	0.06	1425° water quenched	0.00388
5/8-in. weld and plate	12.1	0.10	0.37	0.43	0.15	1425° furnace cool	0.01655
5/8-in. plate (0.22 Al)	12.6	0.08	0.45	0.37	0.10	1425° water quenched	0.01713

Size Corrosion Test Samples, 7/8 in. × 1 7/8 in. × 3/8 in.
Test: Five 48-hr. periods in boiling 65% nitric acid. Acid renewed for each period. Penetration rates given are average for five periods.

containing chromium less than 10% for its beneficial effect on creep strength. Nickel in percentages up to 3% is sometimes added for improvement in physical properties, but the welding of these steels is beyond the scope of this chapter. Table 1 shows the most important properties of some commercial types in general use.

METALLURGICAL AND PHYSICAL PROPERTIES

Welding metallurgy, in general, is covered in the chapter on that subject, but the chromium steels have special characteristics which largely govern their weldability.

Chromium in amounts as great as 3% markedly increases the sluggishness of transformation, thus reducing the cooling rate required to produce a given hardness. Chromium additions above 4% add little to the hardenability (see Table 3). Within the range from 3 to 14% chromium, these steels are hardened intensely by air cooling, an annealing treatment being required to eliminate martensitic structure. A retarded cooling rate produced by preheating 5% chromium steel when welding (see Fig.12) has little effect on the hardness of either the weld metal or heat affected zone.

Chromium favors the existence of ferrite, and as it is increased above 14%, the alpha gamma transformation is gradually eliminated from these steels, so that a single phase alloy of ferrite finally results (at 17 to 18% chromium with carbon under 0.10%). The proportion of martensite and ferrite in a transition alloy varies with the composition, carbon having the greatest influence in promoting martensite. Referring to the constitutional diagram, Fig. 2, showing the structures in steels of various carbon and chromium contents in 1/2-in. squares air-cooled from 1830°F., the effect of carbon on extending the martensitic range toward the higher chromium alloys is readily apparent. Above 18% chromium, the maximum carbons specified for the commercial types are not sufficient to cause perceptible air-hardening. For welding, the carbon should be held under 0.10% in the martensitic steels, but higher carbon is beneficial in the ferritic steels for reducing grain size and brittleness.

Table 3—Brinell Hardness Values of Quenched Chrome Steels

Quenching Temperature	4–6 Cr-0.5 Moly. No. 1	12–14 Cr Type 410 No. 2	12–14 Cr Non-Hard No. 3	15–16 Cr No. 4	16–18 Cr No. 5	23–30 Cr No. 6
No heat	133	133	129	157	155	137
1200°	135	144	120	152	141	130
1300°	135	142	126	154	151	140
1400°	143	150	122	158	151	136
1450°	139	148	123	156	153	144
1500°	235	175	124	155	151	134
1550°	343	307	120	150	154	130
1600°	352	323	121	166	155	132
1650°	365	365	129	181	158	120
1700°	363	373	126	187	172	118
1800°	370	409	141	234	194	115

Material No.

1 5.36% Chromium, 0.47% molybdenum, 0.13% carbon
2 12.89% Chromium, 0.09% carbon
3 13.41% Chromium, 0.22% aluminum, 0.09% carbon
4 15.68% Chromium, 0.10% carbon
5 17.41% Chromium, 0.10% carbon
6 25.71% Chromium, 0.16% carbon

Since the ferritic steels are single phase alloys, they do not respond to heat-treatment and the heat effect of welding results in grain growth in the affected area of the base material with no refinement of underlying beads. The columnar grains of ferrite have an inherent weakness between cleavage planes, reducing the ductility and impact strength. The contrast in grain size between martensitic and ferritic weld metal is apparent in Figs. 3 and 4, respectively. The difference in structure is also very marked at high

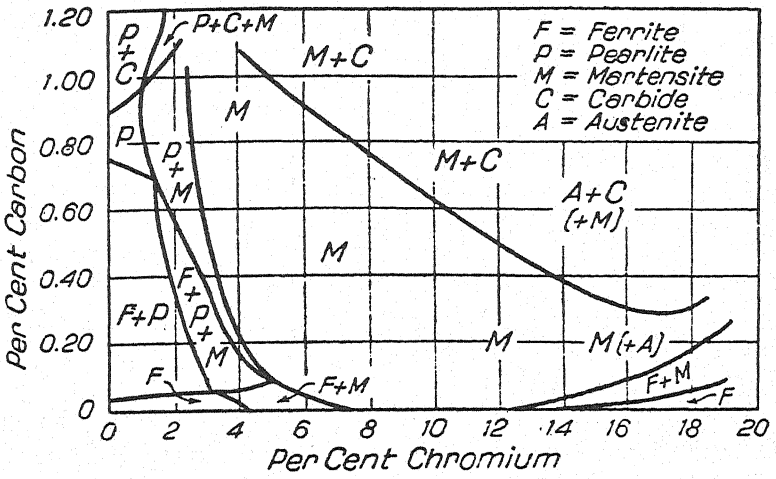


Fig. 2—Constitutional Diagram for Chromium Steels (E. C. Bain and M. A. Grossmann)

magnifications, and is very apparent if the photomicrographs in Figs. 6, 7 and 8 are compared with those in Figs. 9, 10 and 11. Although the ferritic steels are similar to the chrome-nickel austenitic steels in that they do not respond to heat treatment, there is no similarity in the physical properties of their unrefined weld metals. The austenitic steels are remarkably tough and ductile. Brittleness of chromium welds increases as the chromium content is increased above 15%. Above 20% chromium, the impact strength of weld metal, as measured by standard impact tests, is practically zero. Nitrogen, when added in amounts equal to $^1/_{100}$ of the chromium content, is effective in preventing grain growth and increasing toughness. Apparently nitrogen acts in a similar manner to carbon in

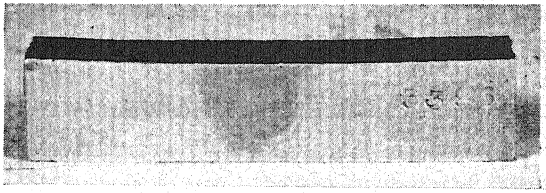


Fig. 3—Photomacrograph of 5% Chromium-$^1/_2$% Molybdenum Weld in $^3/_4$-In. Plate. Deposited Metal Analysis 4.36 Chromium, 0.46 Molybdenum, 0.13 Carbon

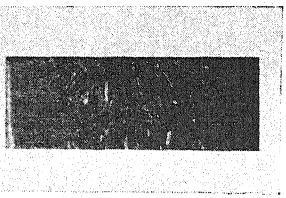


Fig. 4—Photomacrograph of Weld in 25% Chromium Plate. Deposited Metal Analysis 23.7% Chromium

this respect without adversely affecting the corrosion resistance of the metal. Higher percentages of nitrogen, because of limited solubility, may result in objectionable porosity in the welds.

Non-hardening agents, such as columbium, titanium and aluminum, have been used to some extent in base material to reduce the hardenability of the martensitic steels. Columbium and titanium combine with the carbon, nullifying its capacity to harden, and a structure of ferrite, which has the undesirable physical properties of higher chromium ferrite, results. Mechanical working is required to realize satisfactory toughness. For this reason, the use of non-hardening agents in filler metal has been greatly restricted. Aluminum has somewhat the same effect as columbium and titanium in favoring the existence of ferrite and reducing hardenability.

The cast structure of chromium ferrite can only be improved by mechanically working the metal, either hot or cold. Figure 5 shows the macrostructure of 16% chrome weld metal, each bead of which has been severely peened while at a red heat. Structure of this type has a considerably higher impact strength than the large grain structure shown in Fig. 4, which is normal for weld metal of the same analysis that has received no mechanical working.

Because of the brittleness of high chromium steels, castings containing chromium above 15% are seldom used for pressure service. Plate material is considerably improved in impact strength and ductility by the working it receives in rolling. The grains are refined and elongated in the direction of rolling (see Fig. 11), resulting in improved ductility and toughness in a

direction parallel with the surface of the plate. The ductility of the ferritic steels is greatly improved when heated to temperatures as low as 250°F. This phenomenon, which is yet to be satisfactorily explained, greatly facilitates the fabrication of these alloys and is utilized extensively for preventing cracks while welding. Brittleness of the ferritic steels is increased by holding in the temperature range from 850 to 1000°F.; therefore, welded vessels are usually removed from the furnace and air-cooled through this range following an annealing treatment (see Fig. 24).

Chromium is primarily added to steel in amounts over 3% to improve oxidation resistance (see Fig. 1) and corrosion resistance (see Table 2). In amounts less than 3%, chromium is added to tool steels for improvement in physical properties and to some of the low alloy welding steels for its beneficial effects on both physical properties and corrosion resistance. Above 3%, chromium is of little value for improving physical properties at room temperature, except when higher carbon is used to intensify its effect (as in the case of cutlery and die steels).

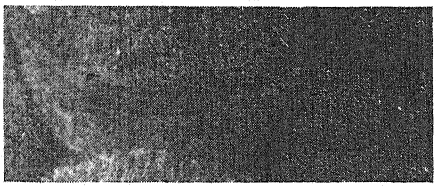


Fig. 5—Photomacrograph of 16% Chrome Weld Heavily Peened

Other properties of chromium steels affecting weldability are thermal conductivity, which drops sharply with increasing chromium (see Fig. 28): electrical conductivity, which is reduced by the addition of chromium (see Metallic Arc Process); and thermal expansion, which is slightly greater than mild steel. Table 3 shows the effect of chromium on the hardness of these steels after quenching. The physical properties of these steels, as compiled by Metal Progress, have been reproduced in Table 1.

WELDING PROCEDURE—FILLER METAL

The best procedures to follow for a given welding problem depend largely on the choice of filler metal. Generally, when proper preheating equipment is available and annealing is planned, a filler metal of approximately the same analysis as the base material is recommended. A great quantity of equipment, including many pressure vessels welded in this manner, has been operating in service successfully for a number of years. Any exceptions to this rule are given below for the separate alloy types. When the conditions are such that annealing is not practical, then the use of an austenitic chrome-nickel steel filler or metal is recommended.

The choice of filler metal is governed by a number of other important factors:

1. The coefficient of thermal expansion of the chromium-nickel steels is considerably greater than it is for the straight chromium steels, and if filler metal of this type in chromium steels is annealed, the full benefits of stress-relieving are not realized because of stresses which are set up upon cooling. Whether or not such stresses are dangerous depends upon the nature of the service. The possibility of stress-corrosion should be considered. Where frequent and large variations in temperature are anticipated, allowance should be made for these stresses to guard against fatigue or corrosion-fatigue failures.

2. The existence of a brittle zone in the heat affected area of unannealed welds should be recognized, regardless of the type of filler metal used.

3. When a dissimilar filler metal such as chrome-nickel steel is employed, there exists the possibility of electrolytic corrosion from galvanic action. Whether or not this is of sufficient importance to be considered, depends, of course, on the nature of the corrosive environment, and frequently must be proved by tests in actual service.

4. Although under certain conditions local stress-relieving or annealing is possible for these steels, it is usually not advisable when it can be avoided. For this reason, emergency field repairs are usually made with 25–12 or 25–20 chrome-nickel filler metal. For field welding pipe or tube joints, the choice of filler metal and question of local heat-treatment depend entirely on the service. The loss of ductility and corrosion resistance in the ferrite steels in the zone which only reaches 850 to 1000°F. during local annealing, should not be overlooked.

5. The dangers of carbide precipitation in austenitic filler metal when annealing in accordance with recommended procedures for chrome steel should not be overlooked. A stabilized filler metal is frequently used to avoid trouble from this source. Although the stabilized chrome-nickel steels require higher temperatures for annealing than are recommended for some of the straight chromium steels, they retain highly satisfactory corrosion resistance after heat treatment at lower temperatures.

Some rules of welding procedure apply in a general way to all of the chromium steels. The same designs, including types of welding grooves, that are used for carbon steel usually can be employed for the chromium steels. Because of the dangers of cracks developing at the root of the weld, welded single "V" joints welded from one side should be used only when absolutely necessary and then with backing-up strips. With normal fabrication tolerances in fit-up fillet welds cannot be considered as reliable as they are for carbon steels. A poor fitting backing ring, or a wide space between members at the root of a fillet weld, frequently can be blamed for cracks originating in the first bead of weld metal.

Preheating is a most important phase of welding procedures, involving straight chromium filler metal deposited by the metallic electric arc process. Preheating as a separate operation is usually not required for processes such as the oxyacetylene, atomic hydrogen and submerged melt (Unionmelt). (See Welding Processes.) Specific recommendations on the different chromium ranges follow.

3 to 10% Chromium Steels

Steels within this range of chromium are intensely air-hardening. Preheating to a minimum temperature of 400°F. is recommended, but the higher the better. Because of the sluggishness of these steels in their transformation, preheating does not serve to reduce the final hardness at room temperature in the unannealed condition (see Fig. 12). The safest procedure is, therefore, to not allow the welds to cool before annealing.

These steels have been extensively used for high temperature service, with the addition of about 0.5% molybdenum for increasing the creep strength. The analysis of the base material, with or without molybdenum, is readily duplicated in the deposited metal, and many specifications contain this requirement. After annealing, the welds possess excellent ductility and impact strength (see Table 4). Coated electrodes that compare favorably with carbon steel electrodes for welding in the vertical and overhead positions do not seem to be available commercially, so that, if pos-

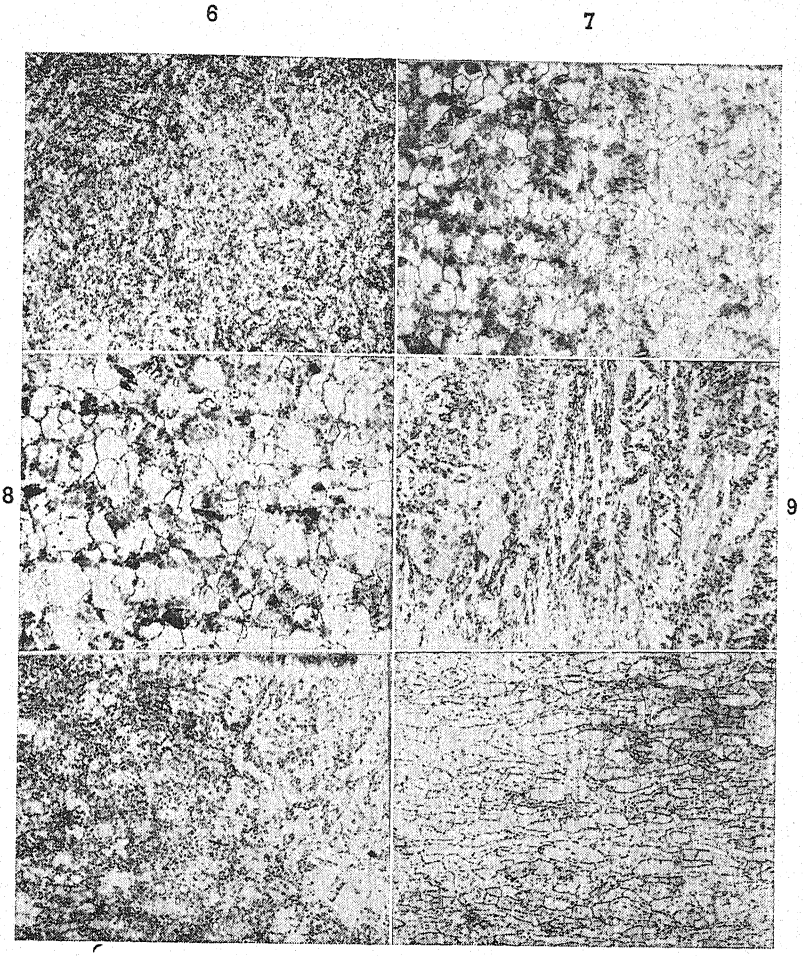


Fig. 6—4–6% Cr-0.5% Moly Weld Metal—As Welded
Fig. 7—4–6% Cr-0.5% Moly Fusion Line and Affected Area Annealed
Fig. 8—4–6% Cr-0.5% Moly Plate Material Annealed
Fig. 9—16% Cr Weld Metal As Welded
Fig. 10—16% Cr Fusion Line and Affected Area Annealed
Fig. 11—16% Cr Plate Material Annealed

sible, welding should be done in the downhand position. Satisfactory welds in all positions can be made, but welds that must meet the porosity standards of the various welding codes are difficult to achieve in any but the downhand position.

To fully soften weld metal of this analysis requires close control of annealing temperature and cooling rate. A satisfactory anneal includes heating slightly above the critical temperature and cooling slowly (not over 25°F. per hour) down to at least 1350°F., after which the cooling rate may be more rapid, but removing from the furnace above 600°F. is not good practice. A heat treatment that has proved successful for 4–6 chrome-moly piping consists of heating to 1550 to 1600°F., cooling 50 to 100°F. per hour to 1200°F. and air cooling from 1200°F. In Table 5 are shown hardness values to be expected from various heat treatments.

It is often inconvenient or uneconomical to maintain the preheating temperature on all of the welded parts of a vessel or structure until ready for the final anneal, so that one or more interstage anneals are frequently used. In Figs. 13 and 14 are shown physical test results obtained on properly annealed welds of this analysis.

When a heat treatment is not to be applied, welding with an austenitic electrode is, without question, the best solution, and the base metal should be of the non-hardening types.

In Table 6 are given test results on unannealed welds made in 8% chromium-titanium non-hardening steel, using austenitic electrodes stabilized with columbium. The microstructures of a martensitic weld before and after annealing are shown in Figs. 6 and 7, respectively. The line of fusion and heat affected zone is shown in Fig. 7. The macrostructure (see Fig. 3) has the appearance of a completely refined carbon steel weld.

12 to 14% Chromium Steels

The welding procedures for this chromium range are little different from

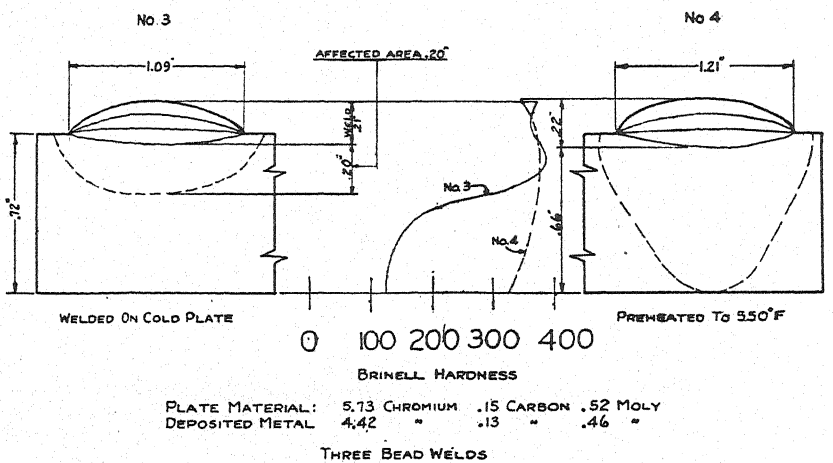


Fig. 12—Hardness of Unannealed Deposited Metal and Affected Plate Area in 4–6 Cr Steel. Made in Three Beads

Fig. 13

Fig. 14

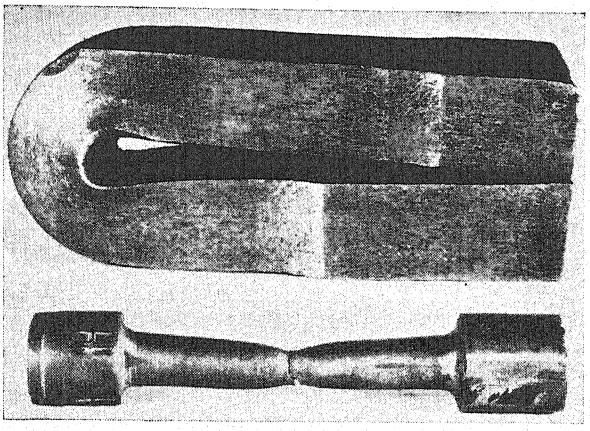


Fig. 13—Bend Test 4.25% Cr-0.5% Moly Weld Metal in 5.31% Cr Plate 3/4 In. Thick. Elongation 54% in Outer Fibers. Without Failure

Fig. 14—All Weld Metal. 0.505 Tension Test in 4.25% Cr-0.5% Moly

Weld Metal: T.S. 77,000 Psi.
Y.P. 63,000 Psi.
Elongation 30% in 2 In.
Reduction Area 61%

Table 4—Test Data of 4-6% Chromium,-0.5% Molybdenum Weld and Plate Annealed

		Analysis			Physical Properties				
	Thickness	Chromium	Carbon	Molybdenum	Y.P. Psi.	T.S. Psi.	Elongation in 2 In. Per Cent	Red. Area Per Cent	Bend Elongation Per Cent
Weld	3/4 in.	4.14	0.12	0.44	58,250	85,250	26	40	63
Plate	3/4 in.	5.10	0.10	0.53	33,000	74,250	33	74	..

Charpy keyhole notch impact value weld metal 20–30 ft.-lb.

Table 5—Hardness Values for 3.5% Cr-0.5% Moly Weld Metal After Various Heat Treatments

Annealing Temperature	Soaking Time	Cooling Rate	Final Hardness Rockwell B
1350°F.	2 hr.	In air	97.0
1400°F.	4 hr.	25°F. per hr. to 1300°F., air cool	88.0
1450°F.	1 hr.	25°F. per hr. to 1300°F., air cool	81.0
1650°F.	1 hr.	25°F. per hr. to 1400°F., 50°F. per hr. from 1400 to 1350°F., furnace cool	80.0

Table 6—Test Data of 1/4 In.-8% Chromium-Titanium Plate Welded with Austenitic Electrodes, Unannealed

Rod	Transverse Tensile Test	Location Failure	Bend Test Elongation
25-20-Cb.	83,500 psi. T.S.	Plate	31.2%
25-12-Cb.	81,300 psi. T.S.	Plate	20.0%

the 3 to 6% range, since they are also martensitic, air-hardening steels (see Fig. 15). Preheating to 300°F. is usually sufficient. The same precautionary measure of annealing before allowing the welds to cool is recommended. The non-hardening types have been used to some extent when preheating is not practical (typical example: spot welded or plug welded linings). The effect on the hardenability of an aluminum addition is shown in Fig. 15. Table 7 gives physical test results of a weld of this analysis, and Figs. 16 and 17 show typical test specimens. Satisfactory annealing is accomplished by soaking at 1250 to 1400°F. It is satisfactory to cool slowly down to 1100°F., but air cooling should begin at this temperature.

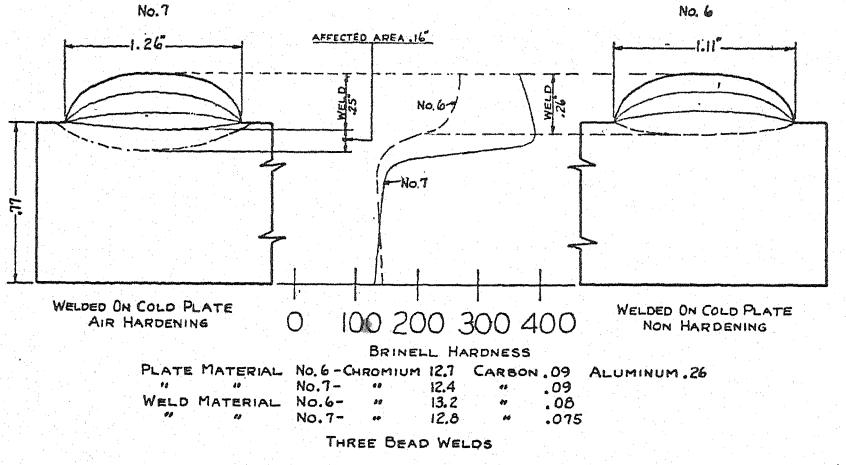


Fig. 15—Hardness of 12-14% Chromium Standard and Non-Hardening Welds and Affected Area Unannealed

The effect of tempering on the properties of a typical alloy in this range is shown in Fig. 18.

Materials in this range are used extensively for oxidation and corrosion resistance at elevated temperatures (typical example: linings for oil refining vessels and related equipment). Since maintaining a preheat on such linings is not practical, an austenitic electrode is normally used and has proved satisfactory for this type of service.

15 to 16% Chromium Steels

This narrow range has achieved special importance in industry because of its excellent resistance to nitric acid and because it is welded with less

Fig. 16

Fig. 17

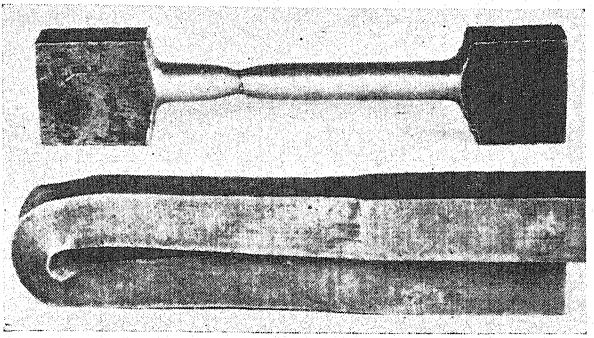


Fig. 16—13.5% Chromium-0.09 Carbon. All Weld Metal. 0.505 Tension Test

Y.P. 57,500 Psi.
T.S. 77,500 Psi.
Elongation 30% in 2 In.
Reduction Area 63%

Fig. 17—13.5% Cr-0.09% Carbon Weld Metal in 12.89% Cr Plate. Elongation in Outer Fibers 75% Without Failure. Plate Thickness 5/8 In.

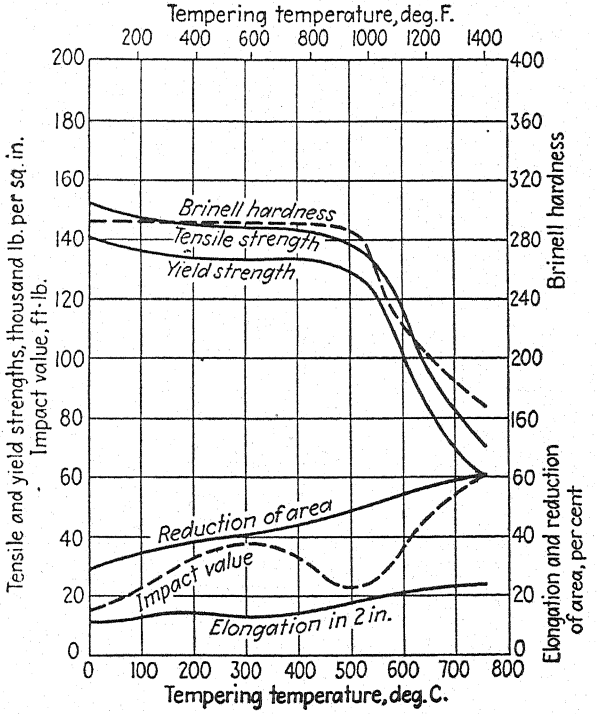


Fig. 18—The Effect of Tempering on a 12.2% Chromium Alloy Quenched from 1850°F. (Giles)

Table 7—Test Data on 12–14% Chromium Weld and Plate Annealed

	Analysis			Physical Properties				
	Thickness	Chromium	Carbon	Y.P. Psi.	T.S. Psi.	Elongation in 2 In. Per Cent	R.A. Per Cent	Bend Elongation Per Cent
Weld	5/8 in.	12.2	0.08	54,200	77,500	30	65	72
Plate	5/8 in.	12.4	0.08	42,000	74,500	37	71	..

Charpy keyhole notch impact value weld metal 20–30 ft.-lb.

difficulty than alloys either lower or higher in chromium. Alloys in this range are less air-hardening than the lower ranges (see Fig. 19), and with the exception of somewhat lower, although satisfactory, impact strength, the weld metal has excellent physical properties. Preheating to 250°F. is usually sufficient, but holding the preheat until the time of annealing is not always essential. Experience must dictate the procedures to follow with respect to preheating. The ductility is enhanced considerably by heating to 250°F. Weld metal of this analysis is frequently too hard to chip with an air hammer and tool before annealing, unless heated to several hundred degrees, and for this reason interstage anneals are frequently used.

Alloys within this range have been used mostly for corrosion resistance.

If the welds are required to have corrosion resistance equivalent to that of the base material, the chromium content of the weld should be as high as that of the plate. On the other hand, for maximum toughness the chromium should be held as low as possible. It is therefore desirable to closely control the analysis within the narrow 1% range usually specified for the plate. Actually, with a given wire analysis it is possible to control the analysis of the deposit within closer limits than the steel mills will guarantee the wire analysis.

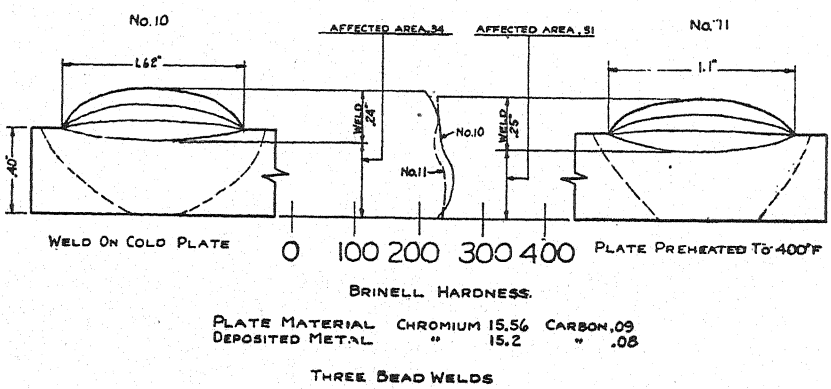


Fig. 19—Hardness of 15–16 Chromium Weld Metal and Affected Area Unannealed

Table 8—Test Data on 15–16% Chromium Weld and Plate Annealed

	Analysis			Physical Properties				
	Thickness	Chromium	Carbon	Y.P. Psi.	T.S. Psi.	Elongation in 2 In. Per Cent	R.A. Per Cent	Bend Elongation Per Cent
Weld	3/4 in.	15.64	0.08	61,250	77,000	32	48	55
Plate	3/4 in.	15.75	0.09	42,500	70,200	42	60	..

Charpy keyhole notch impact value weld metal 12–25 ft.-lb.

Annealing at 1425°F. gives excellent results if soaked for a minimum of 4 hr. up to 1 in. in thickness, with an increase of 1 hr. for each additional inch of thickness. Longer soaking periods are frequently necessary for maximum softness. A satisfactory cooling procedure consists of furnace cooling to 1100°F., followed by air-cooling to room temperature. Figure 20 shows the effect of tempering an alloy of this range at various temperatures. Table 8 shows typical physical test results. Figures 21 and 22

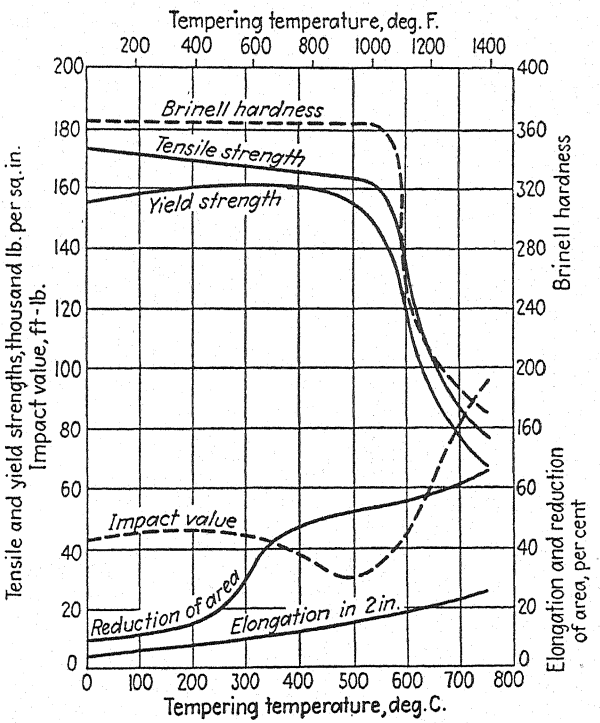


Fig. 20—The Effect of Tempering on a 15.25% Chromium Alloy Quenched from 1850°F. (Giles)

show test specimens illustrating the excellent ductility of annealed welds in this range.

16 to 18% Chromium Steels

Within this range a serious drop in impact strength and ductility occurs with increase in chromium. There is a considerable difference in the brittleness of 16% chromium and 18% chromium alloys. This range is substantially ferritic and non-hardening, as can be seen from Table 3. At

Fig. 21

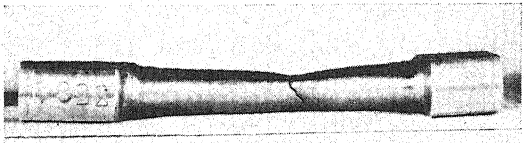


Fig. 22



Fig. 23

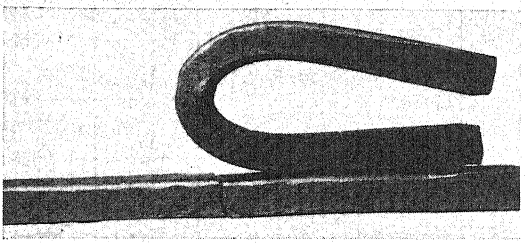


Fig. 21—15.2% Cr-0.08% Carbon. All Weld Metal. 0.505 Tension Test Specimen
Y.P. 59,150 Psi.
T.S. 76,600 Psi.
Elongation 30% in 2 In.

Fig. 22—15.2% Cr-0.08% Carbon Weld in 15.65% Cr Plate. Elongation in Outer Fibers 59.2%. Plate Thickness 5/8 In.

Fig. 23—0.10% Carbon-17.5% Cr Weld in 18.1% Cr Plate. Bend Test Elongation. Unannealed 0%. Annealed 31%

18% chromium, for high impact strength in the welds, an austenitic filler metal of either 25–12 or 25–20 must be used. When using a straight chromium filler metal, preheating to 250°F. will prevent cracking which may otherwise occur due to brittleness. The welding procedures for this range are similar to those for the 15 to 16% chromium range with the exception

that greater care must be used in preheating alloys at the upper limit of the range. The same annealing treatment recommended for the 15 to 16% range is satisfactory for this range. Table 9 gives typical physical results, and Fig. 23 shows physical test specimens from welds of this analysis. Figure 24 shows the embrittlement of steels in this range by holding at various temperatures.

Table 9—Test Data on 16–18% Chromium Weld and Plate Annealed

	Analysis			Physical Properties				
	Thickness	Chromium	Carbon	Y.P. Psi.	T.S. Psi.	Elongation in 2 In. Per Cent	R.A. Per Cent	Bend Elongation Per Cent
Weld	5/8 in.	17.0	0.10	51,000	82,500	18	25	31
Plate	5/8 in.	17.5	0.10	43,500	75,200	32	..	..

Charpy keyhole notch impact value weld metal 5–20 ft.-lb.

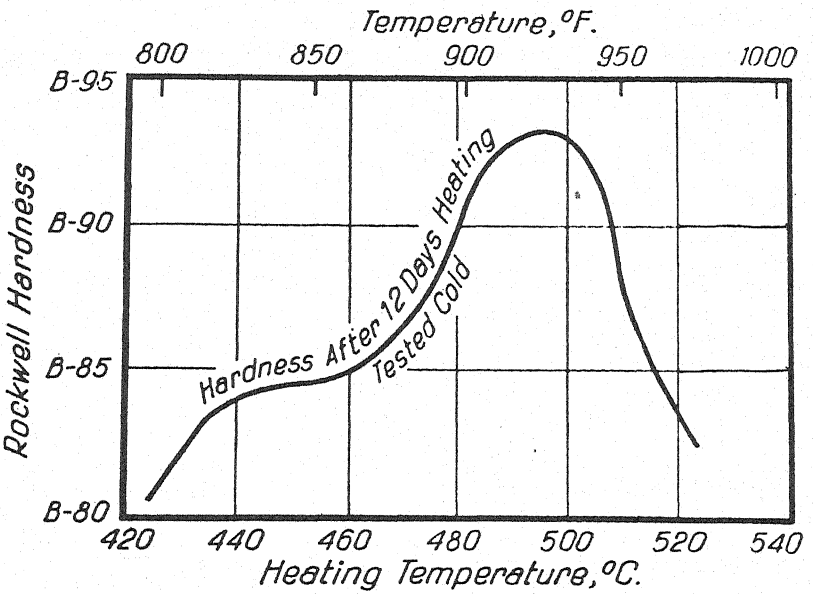


Fig. 24—Curve Indicating Embrittlement by Increased Hardness of 16 to 18% Cr Iron, Low in Carbon. Pieces Were Annealed at 1450°F., Held at Temperatures Indicated 12 Days, Air Cooled and Hardness Measured (Walter M. Mitchell—Book of Stainless Steels)

20 to 30% Chromium Steels

The principal use of the chromium steels above 20% chromium is for resistance to oxidation at high temperatures. Figure 1 shows the excellent resistance of this range in comparison with the lower chromium alloys.

In this range of chromium with carbon under 0.35, these alloys are ferritic and hardenability is negligible. Figure 25 shows the hardness of weld metal and affected zone before annealing.

Weld metal containing chromium in excess of 20% is very brittle and is believed to be unsatisfactory for any practical use. Tests have shown that substantial increase in ductility can be realized by the addition of nitrogen (see Metallurgical and Physical Properties). For the welding which has been done on these steels, an austenitic filler metal, either 25–12 or 25–20, has been most generally used. The addition of nitrogen to plate material for improving physical properties and limiting grain growth is accepted as general practice (see Table 10). Preheating above 300°F. will keep the material in a ductile state while welding. For maximum ductility, it is necessary to soak for 10 hr. or more at 1600°F., followed by rapid quenching.

The brittleness of this range and susceptibility to grain growth have greatly restricted its use. For the same reason, alloys in this range are the least weldable of the chromium steels, and in comparison with other ranges have been little used where applications require welded construction. The bend test in Fig. 26 shows the poor ductility of 25% chromium weld metal after annealing. In comparison, the plate material is shown to possess much greater ductility. Weld metal of the same analysis containing nitrogen has given elongations as high as 25% in similar bend tests. Figure 27 shows a typical weld fracture in 25% chrome weld metal. Note the large columnar structure. The impact strength of this weld, using a Charpy specimen, was practically zero.

WELDING PROCESSES

In general, most of the welding processes used for carbon steel are applicable to the chromium steels. The chapters on Welding Processes describe the different ones in detail, but noteworthy features as they are applied to chromium steels are outlined in the following paragraphs:

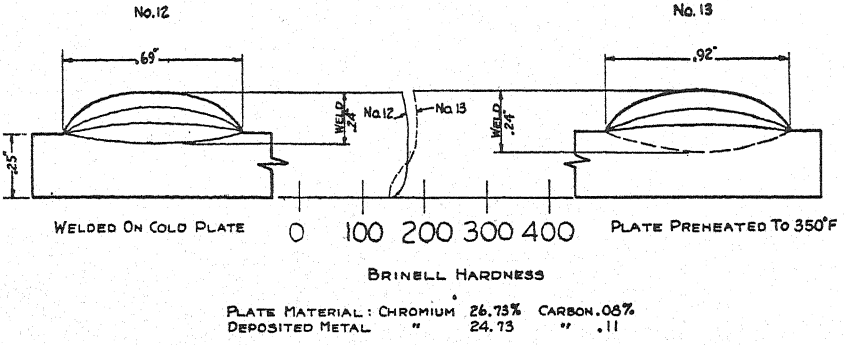


Fig. 25—Hardness of 23–30% Chromium Weld Metal and Affected Area Unannealed

Table 10—Effect of Nitrogen on Physical Properties of 22.4% Chrome, 0.10% Carbon Steel (R. Franks)

Property	Nitrogen Per Cent	
	0.032	0.21
Tensile strength, psi.	77,600	85,000
Yield strength, psi.	46,500	54,000
Elongation in 2 in., per cent	30	29
Reduction of area, per cent	60	66
Izod impact, ft.-lb.	4	24
Brinell hardness	149	166

Heat treatments: water quench from 1650°F. after soaking 6 hr.

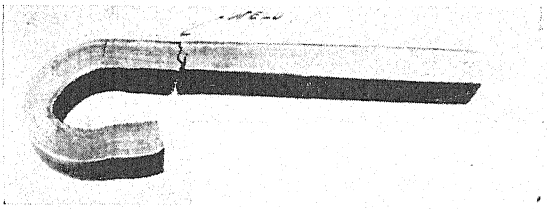


Fig. 26—25.1% Cr Welding. 24.2% Cr Plate Annealed 10 Hr. at 1600°F. Water Quenched. Failure Occurred in Weld Metal with Practically Zero Elongation. The Plate Material Shows Some Ductility



Fig. 27—Weld Fracture in 25.1% Chromium Weld Metal Showing Large Columnar Structure

Oxyacetylene Process

This method requires a special flux capable of dissolving the highly insoluble oxides of chromium. Such fluxes have been developed and are available. The flame should be neutral to prevent oxidation or carbon pick-up in the weld, either of which is detrimental to the quality of the weld. As an exception, a slightly carburizing flame can be used for the 20 to 30% chromium steels. Proper fusion is difficult to obtain with an oxidizing flame.

Because of the low thermal conductivity of these steels (see Fig. 28), they are easily overheated, resulting in boiling of the metal. Porous welds will result if the pool is allowed to boil. This can be avoided by using a

relatively small flame consistent with the plate thickness and giving careful attention to flame manipulation. The danger of grain growth in the base material has limited the use of this process for the ferritic alloys. Travel of the flame should be made as rapid as possible to avoid excessive grain growth when welding the ferritic steels. This process has the advantage of assurance that sufficient preheat has been used to avoid cracking troubles, since preheating is a prerequisite of the process.

In developing proper welding procedure with this process, checks should be made on the physical properties and chromium analysis to make sure that the proper flame and welding technique are being used.

Atomic Hydrogen Process

This process is used successfully for welding the chromium steels, but its advantages probably have not been fully investigated. Excellent welds can be made without the use of a flux, but careful flame adjustment is required to prevent oxidation of the chromium. Sound welds having exceedingly good ductility after heat treatment have been made on 4 to 6% chrome-moly analysis, using base wire filler metal of the same analysis. It has special advantages for welding light sheet, but distortion on thin sheet is usually greater with this process than with the metallic arc process. Heat from the arc usually supplies sufficient preheat to the weld, but the same dangers of overheating and grain growth exist when welding the ferritic steels as are present when welding with a gas flame. Figure 29 shows a special application for which this process has been used. For applications of this type this process has an advantage in that no filler rod is re-

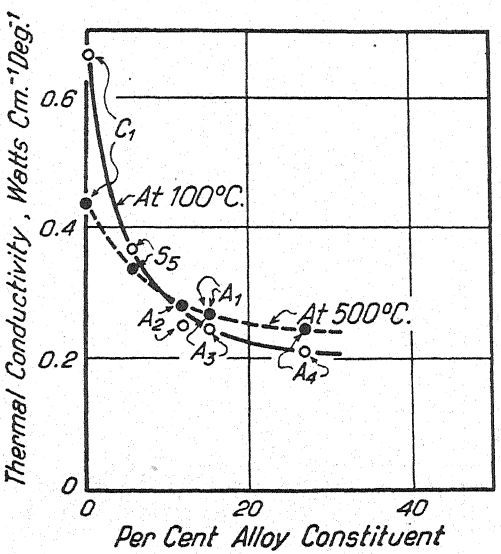


Fig. 28—Decrease in Thermal Conductivity with Increasing Chromium (Shelton and Swanger)

quired. However, when fit-up is poor, a filler rod can be used advantageously with this process. Care must be used to avoid grain growth through overheating when welding the ferritic steels, and there is danger of boiling the metal by holding the flame too long in a local area. Data on cost and special features of operation are given in a special chapter on this process and can be used in general as applying to the chromium steels.

Metallic Arc Process

Coated electrodes are used almost exclusively with the metallic arc process. A number of weld rod coating companies have electrodes available for welding all ranges of the chromium steels. A satisfactory electrode should consistently deposit metal within the range desired. Some loss in

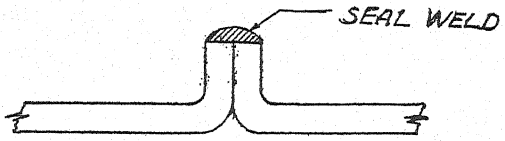


Fig. 29—Application of Atomic Hydrogen Process to Welding of Thin Sheets

chromium occurs in the arc which must be allowed for in the analysis of the wire material. Changes also occur in the other elements, the extent of which varies with electrodes of different makes. Table 11 lists the difference in analysis between the wire material and deposited metal for one make electrode. Wide variations in current and arc length should be avoided, but these factors are not critical for most electrodes. In order to prevent carbon pick-up, materials containing carbon are seldom used in coatings for these alloys. Adjustments in analysis are frequently made by addition of alloys to the coating. This is a convenient method of supplying molybdenum to the weld metal when the analysis specification requires it. The coating should contain materials capable of dissolving chromium oxide, which is a quality that some of the early alloy electrodes lacked.

Electrodes larger than $^{3}/_{16}$-in. in diameter are seldom used for these alloys. It is best to avoid heavy beads when welding the ferritic steels. The low electrical conductivity of the chromium steels limits the length of electrodes in proportion to the diameter, and acts as a natural governor against the use of excessively high currents. Direct current is usually the most suitable for these alloys, but satisfactory welds can be made with alternating current when the electrode has the proper characteristics for maintaining a steady arc with little splatter.

Sound welds with properties satisfactory in all respects can be produced with this process. High quality welds can be produced in all positions, but porosity is difficult to completely eliminate in any but the downhand position.

In this process, properties of the deposit are largely determined by the characteristics of the coated electrode, and the quality of the weld is prob-

ably less dependent on the operator than in any other process of manual welding.

Submerged Melt (Unionmelt) Process

This process can be used for welding chromium steels on applications similar to those for which it has been successful on carbon steels. No preheating is required, even for the air-hardening low chromium ranges, which is a distinct advantage for this process. Very little warping from shrinkage is another advantage of this process. Welding wire of approximately the same composition as the base material should be used. The exact composition of the wire necessary to duplicate the base material analysis in the weld metal should be determined by experiment. A flux (melt) similar to the types used for welding carbon steel is used. The manufacturer should be consulted for recommendations on the type of melt best suited to the alloy to be welded. Excellent physical properties can be obtained by means of this process.

Table 11—Showing Loss in Chromium and Change in Content of Other Elements During Process of Deposition. Analysis Taken from Production Test Samples

	15–16% Cr Iron Weld			
	Chromium	Carbon	Manganese	Silicon
Rod Material, %	16.67	0.08	0.37	0.28
Deposited Metal, %	15.51	0.08	0.23	0.27
Loss, %	1.16	0.00	0.14	0.01
	4–6% Cr, 0.5% Moly. Weld			
	Chromium	Carbon	Manganese	Silicon
Rod Material, %	5.47	0.10	0.34	0.44
Deposited Metal, %	4.42	0.13	0.55	0.27
Loss or Gain, %	−1.05	+0.03	+0.21	−0.17

WELDING DISSIMILAR METALS

Dissimilar metals are frequently used in the same vessel or piece of equipment. This is often highly desirable for maximum economy, but sometimes leads to welding difficulties unless the design engineer has some knowledge of the welding problems involved and the welding procedure is supervised by someone thoroughly familiar with the characteristics of the materials to be joined. In the space allotted for this subject, it is impossible to do more than briefly mention a few of the combinations most frequently used.

Heat exchangers, air preheaters and steam superheaters frequently include in their construction as many as three dissimilar alloys in addition to

carbon steel. Lugs, brackets, bases and other outside attachments to tanks and pressure vessels are usually made of carbon steel. A list of combinations used extensively includes any two of the chromium steels together, any one of the chromium steels to a chrome-nickel austenitic steel, and any one of the chromium steels to carbon steel or one of the low alloy steels.

For any combination, alloying between the base materials and the deposited metal cannot be avoided and the choice of a satisfactory electrode depends primarily on the predicted effect of alloying with the deposit some portion of the two materials being welded. The final proportion of electrode deposit and fused base material in the weld is dependent on several factors, including the thickness of plate, size of electrode, technique of welding and shape of the welding groove. With so many variables affecting the final analysis, ample allowance should be made in the electrode to compensate for the worst condition.

For welding together any two of the chromium types, an electrode normally used for welding either type can be used satisfactorily if followed by heat treatment suitable to both steels. This solution presupposes the use of welding procedures that have proved satisfactory for both of the alloys. If the weld is not to be annealed, an austenitic electrode sufficiently high in chromium and nickel, to allow for the change in composition resulting from alloying, is most suitable. Either a 25–12 or a 25–20 chrome-nickel steel electrode may be satisfactory, the choice depending on the particular combination involved and the service requirements.

For welding any of the chromium types to an austenitic type, the electrode to be used is obvious. An austenitic electrode high in chromium and nickel to offset alloying should be used.

For welding any one of the chromium alloys to carbon steel or a low alloy steel, the choice lies among chromium steel, chrome-nickel austenitic steel, carbon steel and a low alloy steel. For reasons previously explained, a 25–12 or 25–20 electrode should be used for welds that are not to be annealed. The use of either a chromium steel electrode, a carbon steel electrode or a low alloy electrode requires that procedures be used that have proved satisfactory for the martensitic steels and presupposes annealing of the completed weld.

The macrostructure of a weld between 17.5% chromium steel and carbon steel is shown in Fig. 30. Although the electrode used deposited weld metal of 16% chromium, the chromium content of the first bead was sufficiently reduced by alloying with the carbon steel to bring it within the martensitic range. It is apparent from the marked difference in structure that the succeeding layers remained predominantly ferritic. The proportion of base material in the first bead as a result of alloying is usually greater than in other beads of the weld. The band of large grains in the carbon steel adjacent to the deposited metal forms a decarburized zone of ferrite resulting from carbon migration toward the chromium steel during heat treatment. A high concentration of carbon at the edge of the weld from this cause has been known to result in a brittle zone in the weld. The possibility of carbon migration and its consequences should be considered for any weld between chromium steel and carbon steel, or between chromium steel and a low alloy steel, if the temperature of operation is high. Time

and high temperature are both factors favoring migration. Tests have indicated that carbon migration will take place at temperatures as low as 800°F. over long periods of time, and that the speed of migration increases rapidly with increase in temperature. Annealing treatments for short periods of time may cause migration to a degree such that it can be detected

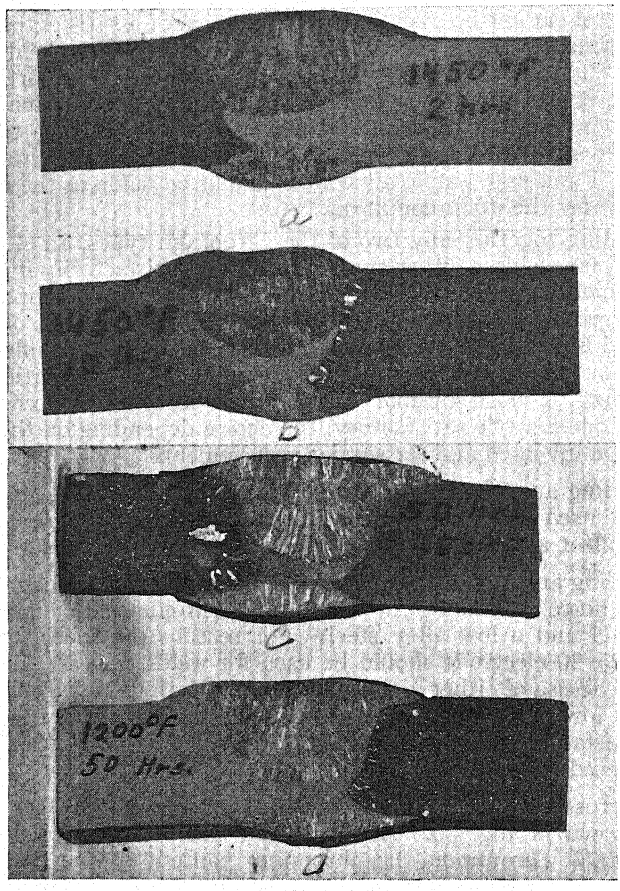


Fig. 30—Photomacrographs of Weld Between Carbon Steel and 17.5% Cr Iron Using 16% Cr Weld Metal

a—Treated 2 Hr. at 1450°F.
b—Treated 10 Hr. at 1450°F.
c—Treated 50 Hr. at 1450°F.
d—Treated 50 Hr. at 1200°F.

under the microscope, but there is usually no appreciable loss in ductility.

Referring to Fig. 31, it is of interest to observe the effect on the hardness variations in weld metal when an austenitic electrode is used for welding chromium steels.

The microstructure shown in Fig. 32 points out clearly that considerable alloying takes place in welded joints. Here is shown the top, middle and bottom beads of a butt weld on 27% chrome plate with 25–12 chrome-nickel austenitic electrodes. The middle bead, line of fusion and 27% chromium plate directly adjacent to the middle bead are also shown in this figure. Of the three deposited beads, only the top is characteristic of a truly austenitic deposit. The middle and bottom beads consisted of both austenite and ferrite. The bottom bead consisted of austenitic dendrites with what appeared to be a pseudo eutectic of austenite and ferrite as filler for the dendrites.

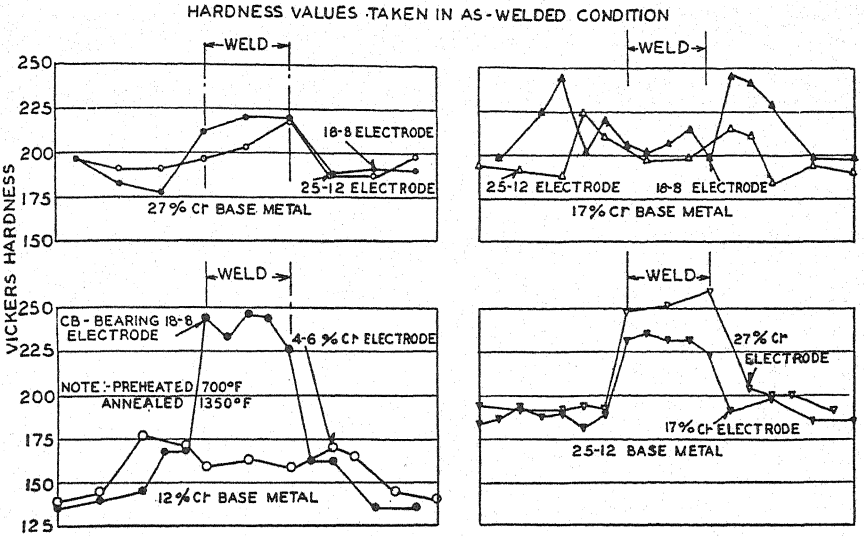


Fig. 31—Hardness Tests of Welds in Chrome Steel Plate Using Filler Metal of Different Analysis

TESTING

Much welded equipment, including many pressure vessels, has been manufactured of the chromium steels from 3 to 18% chromium. Production tests have generally included physical tests, radiographic examination, corrosion tests and chemical analysis.

Physical Tests

Results of physical tests given in this chapter are indicative of the quality of welds possible to obtain in these materials. The physical tests usually specified include transverse tension test, all-weld metal tension test, bend test and specific gravity test. Specimens are usually prepared and tested in accordance with the A.S.M.E. Unfired Pressure Vessel Code, Paragraph U-68.

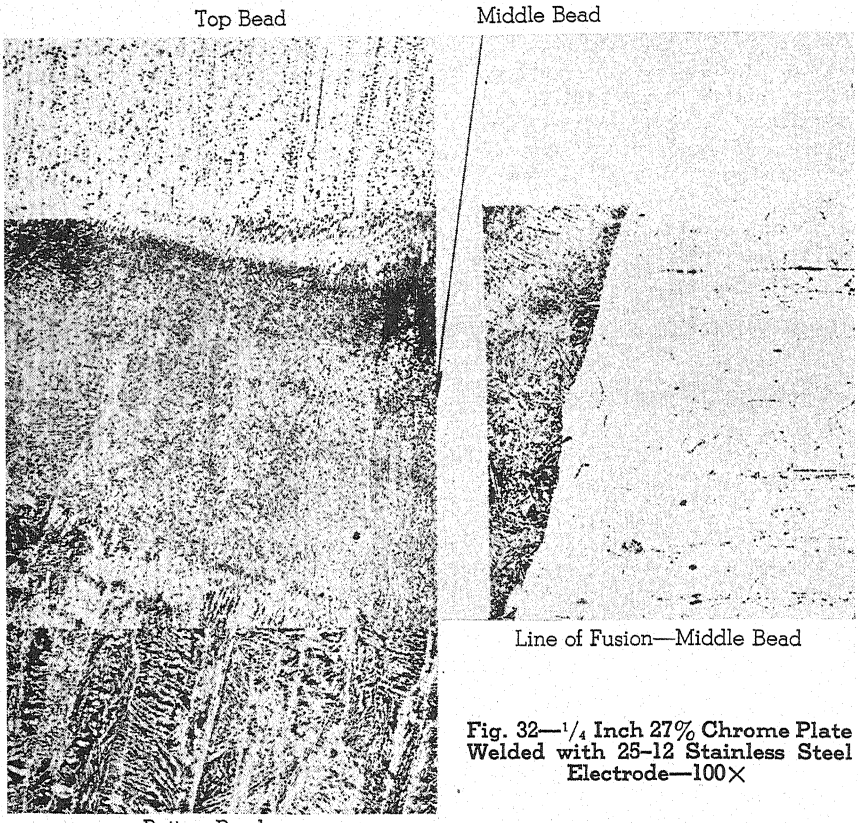


Fig. 32—1/4 Inch 27% Chrome Plate Welded with 25–12 Stainless Steel Electrode—100×

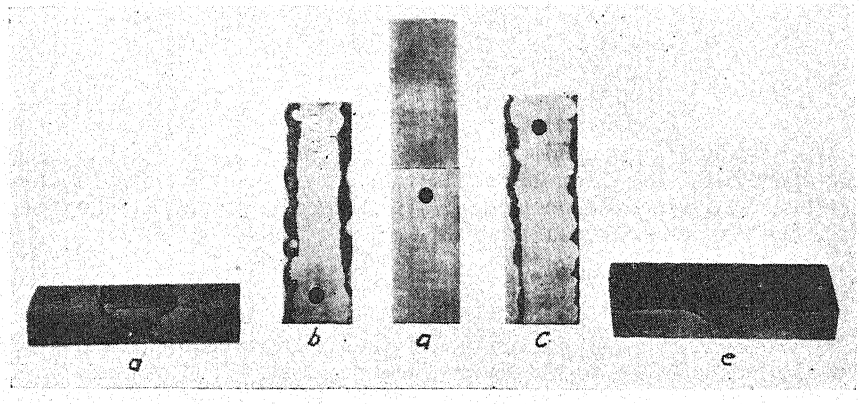


Fig. 33—*a:* 15.5% Chromium Weld and Plate Corrosion Test Specimens After 5–48-Hr. Periods in 65% Boiling Nitric Acid. *b, c, d, e:* 15.5% Chromium Plate 18% Chromium-8% Nickel Weld. Heat Treated 1850°F. Water Quenched

Radiographic Examinations

It is highly important that the main seams of pressure vessels or other equipment for hazardous service be x-rayed for detection of internal cracks. Nozzles and other openings of the inserted type, butt welded to the shell, have been extensively used, thus permitting all welding in a vessel to be x-rayed. Expensive design of this type is warranted for vessels operating in service for which repair welding in the field with austenitic electrodes is undesirable. This is generally the case for process equipment operating under pressure. Because of the danger of cracks occurring after welding is completed, and before annealing, final x-raying is usually done after annealing.

Welds free of objectionable porosity are not difficult to achieve in the chrome steels. The degree of porosity considered objectionable will depend on the service, but welds which meet the A.S.M.E. Code standards are usually satisfactory for the most rigid requirements. Porosity at or near the inside surface of a weld can result in an accelerated rate of corrosion, therefore, radiographic examination is most valuable as an insurance against failures by corrosion resulting from unsound welds.

Corrosion Tests

The extensive use of the chromium steels for nitric acid equipment has led to the adoption of a standard corrosion test specimen and a uniform procedure involving the use of boiling nitric acid. In Fig. 33 are shown a group of standard specimens used for the Huey test, which consists of boiling the specimen for five 48-hr. periods in 65% nitric acid. The standard test specimen, $^3/_8 \times {}^7/_8 \times 1^7/_8$ in. may be taken either longitudinally with or transverse to the weld. The surface of the specimen is prepared on Fisher's No. 1 paper. For each run the acid is renewed and the specimen cleaned with a rubber eraser and some cleaning powder like Dutch Cleanser. Table 2 gives results of corrosion tests on several chromium analyses. It is apparent from this table that the nitric acid test is a reliable method for determining that the welds contain the proper percentage of chromium.

Several of the specimens in Fig. 33 were from welds having the deposited metal dissimilar to the base material. It is apparent that the proper heat treatment had not been given to the base material. The central specimens, showing excellent corrosion resistance, were from 15.5% chrome welds in plate of the same analysis.

For steels in the lower chromium ranges, from 3 to 6%, the hydrogen sulfide test has been widely used.

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CHAPTER 20A

AUSTENITIC CHROMIUM NICKEL STEELS*

Metallurgy, Physical Properties, Corrosion Resisting Properties, Welding Procedures.

1. METALLURGY

General Characteristics

THE austenitic chromium-nickel stainless steels available commercially have been classified by the American Iron and Steel Institute into the following types:

A.I.S.I. Type Numbers and Analyses for Austenitic Chromium-Nickel Steels

Type No.	Carbon, %	Chromium, %	Nickel, %	Other Elements, %
301	Over 0.08–0.20	16.0–18.0	6.0– 8.0	Mn 2.0 max.
302	Over 0.08–0.20	17.0–19.0	8.0–10.0	Mn 2.0 max.
302B	Over 0.08–0.20	17.0–19.0	8.0–10.0	Mn 2.0 max., Si 2.0–3.0
303	0.20 max.	17.0–19.0	8.0–10.0	Mn 2.0 max., S or Se 0.07 min., Mo. 60 max.
304	0.08 max.	18.0–20.0	8.0–10.0	Mn 2.0 max.
308	0.08 max.	19.0–22.0	10.0–12.0	Mn 2.0 max.
309	0.20 max.	22.0–24.0	12.0–15.0	Mn 2.0 max.
309S	0.08 max.	22.0–24.0	12.0–15.0	Mn 2.0 max.
310	0.25 max.	24.0–26.0	19.0–22.0	Mn 2.0 max.
311	0.25 max.	18.0–20.0	24.0–26.0	Mn 2.0 max.
315	0.15 max.	17.0–19.0	7.0– 9.5	Cu 1.0–1.5, Mo 1.0-1.5
316	0.10 max.	16.0–18.0	10.0–14.0	Mn 2.0 max., Mo 2.0-3.0
317	0.10 max.	17.5–20.0	10.0–14.0	Mn 2.0 max., Mo 3.0-4.0
321	0.10 max.	17.0–19.0	8.0–12.0	Mn 2.0 max., Ti 4 x C min.
329	0.20 max.	23.0–28.0	2.5– 5.0	Mo 1.0-2.0
347	0.10 max.	17.0–19.0	8.0–12.0	Mn 2.0 max., Cb 8 x C min.

It is the intent of this Section to cite only the general characteristics and discuss briefly the metallurgy of the austenitic chromium-nickel stainless steels with respect to its influence on weldability and corrosion resist-

* Prepared by a committee consisting of G. S. Mikhalapov, Taylor-Winfield Corp., *Chairman;* R. H. Aborn, U. S. Steel Corp. Research Lab.; H. J. French, International Nickel Co.; J. C. Holmberg, Heppenstal-Eddystone Corp.; T. R. Lichtenwalter, Republic Steel Corp.; S. M. Norwood, Electro-Metallurgical Co.; W. L. Warner, Watertown Arsenal.

ance. For a more comprehensive study of the metallurgy of these steels reference should be made to the literature on this subject.

Steels of this group are characterized by outstanding resistance to corrosion and oxidation. The element chromium, when added to steel, imparts these characteristics as well as increased strength and hardness at elevated temperatures. Chromium is a strong ferrite former and, when added to steel in the amounts described for this group (16–25%), forms a solid solution of chromium and carbon in alpha iron. The resultant alloy has a ferritic structure which is strongly magnetic.

The addition of nickel, a strong austenite forming element, to the above chromium-carbon-iron alloy in sufficient amounts to give the chromium-nickel proportions described in this chapter, may completely suppress the magnetic ferritic structure to form a structure completely austenitic at room temperature. The resultant austenitic alloy, a solid solution of chromium-nickel-carbon in gamma iron, is non-magnetic in character, and has, in general, a greater utility value than the straight high chromium ferritic steel alloys, because of improved ductility and toughness. The principal effect of nickel in these alloys, in addition to the formation of austenite, is increased resistance to creep and to the reducing type of corrosion. The majority of the alloys in this group are completely austenitic, but for specific applications the austenite and ferrite forming elements of certain commercial alloys covered in this group are not completely balanced, and therefore form a predominantly austenitic structure with a secondary ferrite phase. This type of alloy containing a duplex structure is slightly magnetic and is exemplified by the 25% chromium, 12% nickel composition.

The austenitic steels are not hardened by heat treatment, but are hardened and strengthened by cold-working. Cold-worked steels are relatively ductile, the degree of ductility depending upon the composition and the amount of cold work. These steels can be softened or annealed by heating to temperatures between 1850° and 2100°F., depending on the composition, and cooling rapidly.

The steels that do not contain stabilizing elements such as columbium and titanium, consisting of a single-phase austenitic structure or two-phase structure (austenite plus a smaller amount of ferrite), have their maximum corrosion resistance when the elements are in solid solution (annealed condition). If these alloys are subjected to heat at temperatures between 800° and 1600°F. during welding or forming operations, some of the elements are taken out of solution to form precipitates that may impair corrosion resistance. These precipitates occur at the grain boundaries of the alloys containing totally austenitic and duplex (austenite and ferrite) structures, causing susceptibility to intergranular corrosion. Similar structural changes also occur in the ferrite phase of the alloys containing a duplex structure, causing susceptibility to general corrosion. Since the formation of precipitates to the extent of impairing corrosion resistance is a function of time and temperature, exposure to the sensitizing range (800–1600°F.) in many applications is not sufficient to require subsequent heat treatment. However, the restoration of impaired corrosion resistance is accomplished when deemed necessary by heating the metal uniformly to a re-solution temperature in the range of 1850–2100°F. (depending on the alloy content), holding at this temperature for at least one hour per inch of

maximum thickness and cooling quickly and uniformly. Heat treatment for this purpose is not necessary for Types 321 and 347, which alloys contain titanium or columbium. As shown in the next section, the columbium or titanium which they contain prevents the formation of harmful precipitates, and thus inhibits susceptibility to intergranular corrosion. For pressure vessels the exact treatment is prescribed by the A.S.M.E. Boiler Code Committee and these rules should be consulted for stresses, precautions and the like.

It should be pointed out that alloys containing columbium or titanium as a stabilizing element should have a completely austenitic structure, plus columbium or titanium carbides, at room temperature in order to make the alloy entirely immune to the effect of heat in the sensitizing range (800–1600°F.). If a secondary ferrite phase is present in the columbium and titanium bearing alloys, this phase is subject to structural changes when exposed to temperatures of 800–1600°F. which may impair physical and corrosion-resistant properties. To assure a completely austenitic structure the nickel and manganese contents are generally increased somewhat over the minimum for the range specified. Columbium and titanium are only effective in preventing intergranular corrosion in the austenitic phase, and are not effective in preventing general corrosion in the ferrite phase.

Addition of Special Elements to Austenitic Chromium–Nickel Steels

Many commercial types of austenitic chromium-nickel steels contain modifying additions of special elements. Some of these elements, such as manganese, augment the austenite, stabilizing action of the nickel while others, such as molybdenum, columbium, titanium, are ferrite and carbide formers, the same as chromium. Silicon is also a strong ferrite forming element. The austenite and ferrite forming elements are suitably balanced to meet the requirements for the various applications of these alloys.

The following table indicates the functions of special elements in austenitic chromium-nickel steels.

Special Elements in Austenitic Chromium-Nickel Steels

Special Element	Types of Steel	Effects
Carbon	All types	Promotes the formation of austenite In so far as possible the carbon should be low for best results in service after welding
Columbium	347	Primarily to combine with carbon to reduce susceptibility to intergranular corrosion. Grain refiner Promotes the formation of ferrite, therefore manganese and nickel should be increased to balance alloys containing columbium
Copper	315	Promotes the formation of austenite
Manganese	All types	Promotes the formation of austenite Improves corrosion resistance Improves hot ductility Improves welding characteristics

Special Element	Types of Steel	Effects
Molybdenum	303, 315, 316, 317	Promotes the formation of ferrite, therefore manganese and nickel should be increased to balance alloys containing molybdenum Improves corrosion resistance to reducing media Improves strength at high temperatures Increases machinability
Phosphorus and Selenium, or Sulphur	303	Increases machinability but makes welding difficult Generally lowers corrosion resistance
Nitrogen	All types	Promotes formation of austenite Increases yield point and tensile strength In excess of 0.10% in austenitic steels will increase susceptibility to intergranular corrosion
Silicon	302B	Promotes the formation of ferrite Increases resistance to scaling Minimizes losses of oxidizable products as columbium, titanium and chromium in weld metal
Titanium	321	Primarily to combine with carbon to reduce susceptibility to intergranular corrosion. Grain refiner Promotes the formation of ferrite, therefore manganese and nickel should be increased to balance alloys containing titanium
Tungsten	...	Promotes formation of ferrite Increases high temperature strength and corrosion resistance Chiefly used in valve steels and castings

2. PHYSICAL AND MECHANICAL PROPERTIES

The nominal physical and mechanical properties of the principal types of austenitic chromium-nickel steel are listed in Table 1, Nominal Properties of Wrought Austenitic Chromium-Nickel Steels, and also compared with plain low carbon steel.

These steels can be hot-worked without difficulty at the appropriate temperature by recognizing that they are stronger and stiffer than mild carbon steel and providing for extra power or more blows of the forging hammer. Because of their low conductivity, the heating must be performed more slowly and carefully, and, owing to their stiffness, reheating during hot-working will need to be more frequent than for mild carbon steel. The proper hot-working and annealing temperatures are listed below:

Grade	Forging Temperature		Annealing Temperature	
	Beginning, °F.	Finishing, °F.	°F.	Rate of Cooling
304, 302	2100–2200	1600–1700	1900–2000	Very rapid
316	2100–2200	1600–1700*	1950–2050	Very rapid
321	2100–2200	1600–1700*	1900–2000	Rapid
347	2100–2200	1600–1700*	1900–2000	Rapid
309	2150–2250	1700–1800*	1950–2050	Very rapid
310	2150–2250	1700–1800*	1950–2050	Very rapid

* It is preferable to stop forging at 1800°F., except for final sizing in which any working below 1800°F., should be light.

Table 1—Nominal Properties of Wrought Austenitic Chromium-Nickel Steels

Alloy / A.I.S.I. Type	18-8 304	18-8 302	18-8 Mo 316	18-8 Ti 321	18-8 Cb 347	25-12 309	25-20 310	Comparative Properties of Low Carbon Steel
Typical composition (special elements) Carbon	0.08 max.	0.08–0.20	0.10 max.	0.10 max.	0.10 max.	0.20 max.	0.25 max.	
Chromium	18.00–20.00	18.00–20.00	16.00–18.00	17.00–20.00	17.00–20.00	22.00–26.00	24.00–26.00	
Nickel	8.00–10.00	8.00–10.00	14.00 max.	7.00–10.00	8.00–12.00	12.00–14.00	19.00–21.00	
Other elements			2.00–3.00 Mo	Ti min. = 4 x C	Cb = 10 x C			
Condition described	Soft	Cold-Worked Flat	Soft	Soft	Soft	Soft	Soft	Soft
PHYSICAL PROPERTIES								
Specific gravity, lb./in.³ (70°F.)	0.286	0.286–0.284	0.288	0.285	0.285	0.283	0.288	0.283
Specific heat, Btu./°F./lb. (0–200°F.)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.11
Specific electrical resistance, microhms/in.³ (70°F.)	27.6	28–32	28.5	28	28	30.7	30.5	4.3
Magnetic permeability, μ (70°F.)	1.003	1.1–2.0	1.003	1.003	1.003	1.003	1.003	Ferro-magnetic
Thermal conductivity Btu./ft.²/hr./°F./in. at 200°F.	113	113	108	113	113	95	...	345
Thermal conductivity Btu./ft.²/hr./°F./in. at 1000°F.	153	153	148	156	156	125	...	285
Coefficient of thermal expansion per °F. 0–200°F.	9.6 x 10^{-6}	9.6 x 10^{-6}	9.3 x 10^{-6}	9.3 x 10^{-6}	9.3 x 10^{-6}	8.3 x 10^{-6}	8.0 x 10^{-6}	6.6 x 10^{-6}
Coefficient of thermal expansion per °F. 0–1500°F.	11. x 10^{-6}	11.x 10^{-6}	11.x 10^{-6}	11.x 10^{-6}	11.x 10^{-6}	9.5 x 10^{-6}	9.5 x 10^{-6}	...
Melting range, °F.	2500–2600	2550–2600	2500–2550	2550–2600	2550–2600	2500–2550	2500–2550	2700–2800
MECHANICAL PROPERTIES (at Normal Temperature)								
Hardness Brinell No.	135–185	180–380	135–185	135–185	135–185	150–190	150–200	80–100
Hardness Rockwell No.	B75–90	C5–40	B75–90	B75–90	B75–90	B80–90	B80–95	B45–60
Modulus of elasticity, 10^6 lb./in.²	29	29	29	29	29	29	29	30
Yield strength (0.2% offset), 10^3 lb./in.²	30–45	60–140	30–45	30–45	30–45	40–50	40–50	20–30
Tensile strength, 10^3 lb./in.²	80–95	100–185	80–95	80–95	80–95	90–110	90–110	45–55
Elongation in 2 in., %	65–50	50–4	65–50	65–50	65–50	50–35	50–35	50–35
Reduction of area, %	70–55	...	70–55	70–55	70–55	60–50	60–50	70–55
Endurance limit (fatigue), 10^3 lb./in.²	30–40	50–120	40–45	40–45	40–45	50–55	...	20–30
Notched-bar impact strength (Charpy), ft.-lb.	90–60	60–25	90–60	90–60	90–60	90–60	80–70	50–35
Olsen cupping value, in.	0.500–0.400	...	0.475–0.400	0.475–0.400	0.475–0.400	...	...	0.450–0.400
MECHANICAL PROPERTIES (at elevated temperatures)								
Stress for creep rate of 1% per 10,000 hr. at 1000°F., 10^3 lb./in.²	15–19	...	22–24	17–18	Similar	16–18	16–18	3–7
Stress for creep rate of 1% per 10,000 hr. at 1250°F., 10^3 lb./in.²	4–6	...	6–7	5–6	to 18–8	6–8	5–7	0.3–0.7
Stress for creep rate of 1% per 10,000 hr. at 1500°F., 10^3 lb./in.²	1	...	1–2	1		1	1	...
Short-time tensile strength at 500°F., 10^3 lb./in.²	60–70	80–150	75–80	60–65	65–72	85–90	85–90	65–71
Short-time tensile strength at 1000°F., 10^3 lb./in.²	52–62	70–105	65–70	50–55	58–63	68–72	80–83	25–35
Short-time tensile strength at 1500°F., 10^3 lb./in.²	16–26	25–30	25–32	20–30	25–32	25–32	33–37	2–5
Max. allowable working stress (A.S.-M.E. Code) −20 to 700°F., 10^3 lb./in.²	15	...	15	15	15	...	...	9
Max. allowable working stress (A.S.-M.E. Code) 1000°F., 10^3 lb./in.²	10	...	11.2	10	10	...	...	2
Max. allowable working stress (A.S.-M.E. Code) 1200°F., 10^3 lb./in.²	3.2	...	3.6	3.2	3.2	...	...	...
MECHANICAL PROPERTIES (at low temperatures)								
Notched-bar impact strength (Charpy) at 0°F.	90–60	60–25	90–60	90–60	90–60	90–60	...	30–15
Notched-bar impact strength (Charpy) at −100°F.	90–60	60–25	90–60	90–60	90–60	90–60	...	5–1
Notched-bar impact strength (Charpy) at −300°F.	90–60	...	90–60	90–60	90–60	90–60	...	...

It is important not to go below the hot-work finishing temperatures listed above owing to the tendency of these steels to work-harden while still very hot. This work-hardening tendency is enhanced as the temperature drops, so that cold work will produce marked work-hardening which is a maximum in the 18–8 type as it is the least stable austenite.

The A.S.M.E. Boiler Code Committee permits a maximum allowable efficiency for welded joints in U-68 vessels where the joints are radiographed of 90% and in U-69 vessels where the joints are not radiographed of 80%. These efficiencies are conservative for good gas and arc welds.

3. CORROSION RESISTING PROPERTIES

The austenitic varieties of stainless steels are known to be highly resistant to the action of oxidizing types of corrosive substances. Their resistance to corrosion is explained by the high affinity that chromium has for oxygen. It is the formation of a thin chromium oxide film on the surface of the material which gives the base metal its protection.

The halogen acids, such as those of chlorine, bromine, fluorine and their compounds, ultimately break down this surface film, attacking the base metal and corroding it to the point of failure. However, this does not mean that stainless cannot be used for numerous acid compounds of the above elements.

In some cases, the simple addition of another element, such as molybdenum, to the austenitic alloy will change its corrosion-resisting qualities to such an extent that satisfactory resistance to some solutions is obtained. In other cases, just the addition of another element or compound to the corrosive media to act as an inhibitor is all that is required. An example of this is the hanging of a bag of lime in a circulating calcium chloride brine refrigerating system. Used even before the development of stainless steels, lime has a tendency to keep the solution alkaline and to reduce to a minimum corrosion on all metallic parts. A wealth of specific information on corrosion resistance of stainless steel is to be had for the asking from the producers of stainless materials.

Alloys of the austenitic chromium-nickel types make very satisfactory welds from a physical standpoint. However, under certain corrosive conditions, they tend to show what is commonly called "weld decay." When an austenitic chromium-nickel alloy is reheated to between 800–1600° F., the carbon is precipitated out of solid solution and migrates to the grain boundaries in the form of chromium carbides. These carbides, as well as the adjacent chromium impoverished areas, have a much lower resistance to corrosion than the parent metal and the result is a more rapid attack under certain corrosive conditions.

In the process of welding, the deposited metal and the base metal are brought up to the fusing temperature, approximately 2800°F. Hence, with the actual weld itself at the fusion temperature, there will be a parallel zone somewhere between it and the parent metal being welded that has been heated between 800–1600°F. In this zone will be found the precipitated carbides to which reference has been made. Their number will be very nearly in direct proportion to the percentage of carbon present.

It is said that the 18–8 types of stainless, containing up to 0.02% carbon, will retain it in solid solution. As the carbon content increases—say, to 0.08%—the amount of carbon thrown out of solid solution slowly increases. In most cases, this is not detrimental to the corrosion resistance of the material. However, after a carbon content of more than 0.08% is reached, the migration of the carbon into the grain boundaries increases rapidly and under certain corrosive conditions becomes very detrimental. It is recommended, therefore, that material to be welded should not have more than 0.08% carbon present, unless the application for which the steel is to be used is one in which a zone containing "weld decay" will not be an adverse factor.

The Strauss ($CuSO_4.H_2SO_4$) test is suggested to determine the susceptibility of the material as received to "weld decay." While this test can be used on a welded specimen, it is difficult to interpret on welds where the trouble may be mechanical rather than due to precipitated carbides. Under the circumstances the investigator may be misled by the test results.

Another test for "weld decay" on welds in the welded condition makes use of a solution consisting of 10–20% nitric acid plus 2–4% hydrofluoric acid, the balance water. This test should be made at a temperature of 180°F. and is very drastic as well as rapid. The solution attacks the parent metal in the zone where precipitated carbides are present. The attack is very severe and if the carbides are present in any considerable quantity, only a few minutes are necessary to sever the specimen alongside the weld where the stock is of $^1/_{16}$-in. thickness or less. A specimen with no carbides present will show a uniform attack throughout. Where the carbides are present in greatest number, the attack will show up first as a slight discoloration, and then as a somewhat sandy condition which will steadily increase to the point where grains of the metal can actually be rubbed loose with the finger.

Four periods of $^1/_2$-hr. each in the nitric-hydrofluoric acid test are generally sufficient. However, the results, especially on border-line cases, may be somewhat difficult to determine for those who have not had previous experience. A good way to set up standards is to obtain a number of welded specimens having varying carbon contents starting at about 0.05% and increasing by steps of 0.01% to a maximum of around 0.12%. Here again the investigator must know how to interpret the results of the test and to determine whether the steel will be satisfactory under the service conditions proposed.

NOTE: Nitric and hydrofluoric acids are strong acids and great care should be used in handling. Use approved safety goggles and rubber gloves, making sure they do not leak.

The microscope is a useful means of testing to determine the amount of segregated carbides. A test specimen in the "as-welded" condition and which includes the heat-affected section should be used. The specimen should be highly polished and electrolytically etched by immersing as the anode in a solution consisting of 10 gm. sodium cyanide containing at least 0.20% chloride in 90 cc. of distilled water. The cathode used should be a section of the same or similar material. The general practice is to space the electrodes about 1-in. apart and use an etching time of 5 min. Current from a regular 6-volt automobile storage battery is entirely satisfactory for the test.

The specimen should be removed, rinsed in hot water and dried in a mild air blast so as not to stain. It should then be examined under the microscope at 500 or 1000 diameters. The carbides will appear as short or round globules encircling the grain structure and will be present in varying quantities, governed by the amount of carbon in the parent metal. Highly cold-worked material will also show carbides that have had their migration toward the grain boundaries arrested by the slip planes.

Here again it is important that the investigator know how to interpret his laboratory findings in terms of actual service conditions. After all, there are many fabricated articles of austenitic chromium-nickel material which are giving excellent service despite the fact that considerable segregated carbides are present in the section which has been affected by the heat from the welding operation.

Special Methods of Testing Austenitic Cr-Ni Welds

In addition to the usual test methods applied to welded joints and weld metal, described elsewhere in this book, there are a few special methods or requirements applicable primarily to these grades of steel. These are:

1. Determination of Weld Metal Composition.—This is sometimes required (as in A.S.M.E. Boiler Code Interpretation: Case 897) to insure approximate uniformity of composition throughout the joint when such uniformity is vital to the performance of the joint in service where corrosion is involved.

2. Intergranular Corrosion Test.—This is a test to determine the susceptibility of the welded joint or weld metal to intergranular corrosion in a solution capable of corroding the grain boundary regions of metal sensitized by the heat of welding. Intergranular attack is detected by examination of a bent or twisted surface, by measurement of the change of electrical resistance resulting from intergranular corrosion or by microscopic examination of a polished cross-section after the corrosion test. The test requirements in Case 897 of the A.S.M.E. Boiler Code Interpretations are cited as a typical example.

"The free-bend test specimen shall be ground and polished. Immerse in a boiling copper-sulphate sulphuric-acid solution for a minimum of 72 hr. This solution shall consist of 47 cc. concentrated sulphuric acid and 13 gm. of crystalline copper sulphate ($CuSO_4.5H_2O$) per liter of water. The sample shall be bent so as to confine the bend to a point $1/4$ in. from the edge of the weld in the base metal, and the least elongation in the outer fibers measured across the weld shall be not less than 20%. After bending, the metal shall show no sign of disintegration."

There are several methods that can be used to combat corrosion in a welded article made from an austenitic chromium-nickel steel. In this connection, however, it is necessary that the ultimate user supply the pertinent facts as to how the steel is to be used and cooperate closely with the fabricators as well as with the producer of the material so that the best grade of alloy for the application can be selected.

In fabricated articles of suitable size and shape, the heat-affected zones can be eliminated by annealing. However, the proportions and shape may be such as to make annealing impracticable because the heat would warp the structure so much that it would be useless.

For annealing there must be on hand equipment capable of heating the

structure to between 1950–2050°F. Sufficient time should be allowed to make sure that all parts of the structure are up to temperature and that the carbides are put back in solid solution in the heat-affected zone. The subsequent cooling operation must be rapid from 1950°F., through the critical range to hold the carbon in solid solution once it has been restored by the annealing treatment. Thicknesses of 0.05 in. and lighter can be cooled in the air. However, when the steel is of greater thickness than this, a more drastic cooling must be applied, such as plunging into water directly from the furnace before the structure can cool down to its critical temperature range.

For the past several years considerable work has been going forward on the addition to the austenitic chromium-nickel alloys of so-called stabilizers, such as columbium and titanium. These elements have a higher affinity for carbon than chromium and tend to hold it from migrating into the grain boundaries when reheating to 950–1450°F.

Welded structures using these stabilized types have been giving excellent accounts of themselves where they have been properly used. These stabilized alloys are at their best when used as heat-resisting alloys to work at temperatures of 950–1550°F.

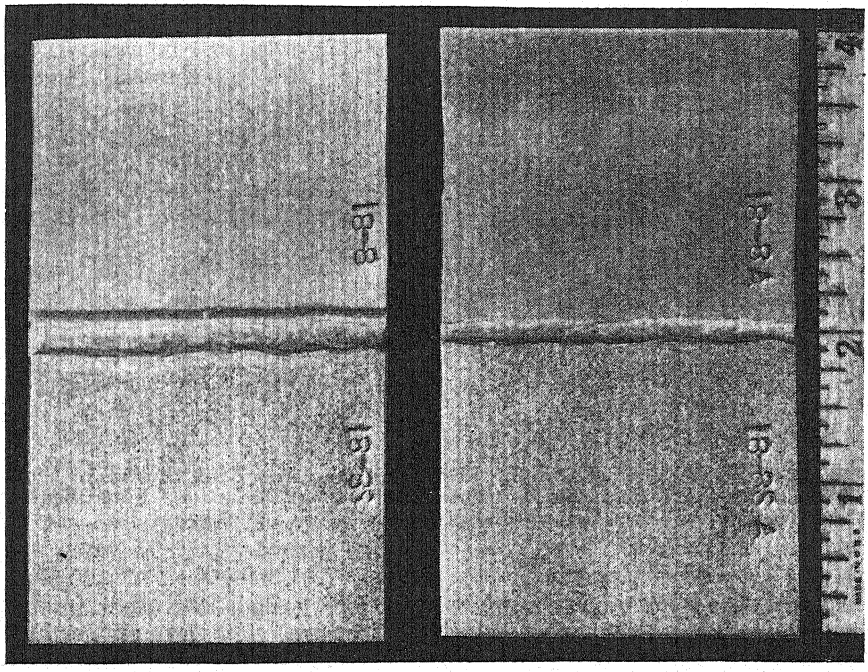


Fig. 1—18–8 Arc Welded to 18–8–S. (Left) As-Welded. Note Carbide Precipitation Area Adjacent to Weld on the 18–8 Sample. (Right) Annealed. Note Absence of Carbide Precipitation Area

Figures 1 to 5 show the effect of carbide precipitation as detected in nitric hydrofluoric solution and microscopic examination of electrolytically etched specimens.

Figure 1 shows two pieces of 18–8 steel (Type 302) welded to two pieces of 18–8-S (Type 304). The pieces marked *A* have been subsequently heat treated at 1950–2050°F. and the other pieces are in the as-welded condition. All pieces have been etched with hot nitric hydrofluoric solution. Note the corrosion-affected zone in the 18–8 as-welded piece caused by carbide precipitation, alongside the weld. The corresponding zone on 18–8-S piece is practically free from corrosion. Note also that the heat-treated pieces are completely free from the corrosion-affected zone, showing that the precipitated carbides have gone back into solution.

Fig. 2—Original Stock Away from Weld Area—18–8. Magnification 500×

Fig. 3—Microsection Through 18–8-S As-Welded and Shown in Fig. 1. Magnification 500×

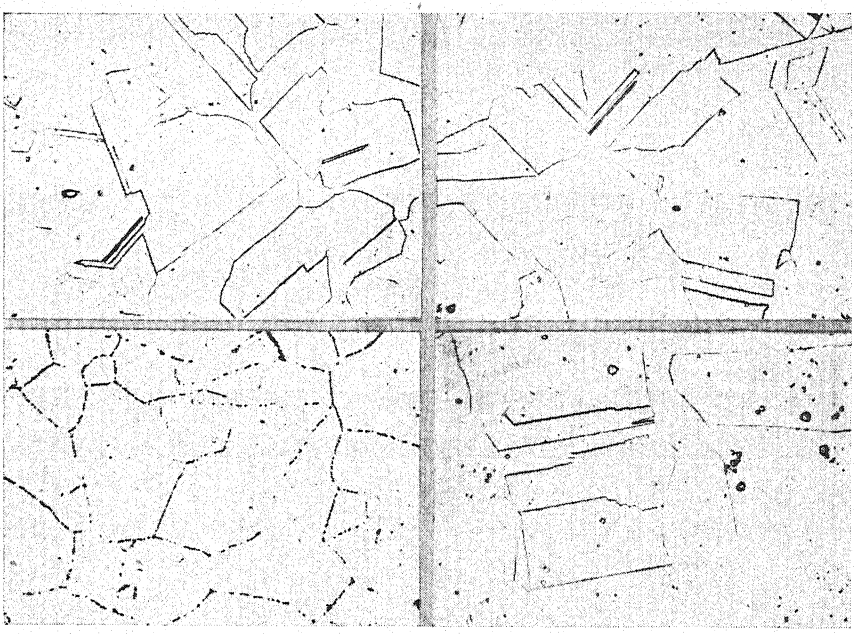


Fig. 4—Microsection Through 18–8 As-Welded and Shown in Fig. 2. Note Carbides in Weld Effect Zone. Magnification 500×

Fig. 5—Same Zone Shown in Fig. 4 After Heat Treating. Magnification 500×

Figure 2 is a photomicrograph of a section through 18–8 stock prior to welding. Figure 3 is a photomicrograph of a section through the heat-affected zone of 18–8-S stock in as-welded condition. Figure 4 is a photomicrograph of a section through the heat-affected zone of 18–8 stock in as-welded condition and Fig. 5 is a photomicrograph of a section through the same zone as in Fig. 4 but after heat treating. Note the presence of carbides along the grain boundaries on Fig. 4.

In making a weld on an austenitic chromium-nickel type of steel, a filler rod should be selected that will give a weld metal which conforms as closely

as possible to the parent metal. The use of a filler rod having a slightly higher chromium and nickel content than the plate is to be preferred to one of lower alloy.

After the welds are completed, all welding flux scale and heat tint should be removed by grinding, pickling or other approved method. It is also very good practice, if the structure is to be annealed, to remove the welding flux from the surface before putting it in the furnace.

If the welds are to be ground flush with the parent metal, all rough grinding can be done using rubber or bakelite bonded wheels and set-up wheels with abrasive and binder using polisher's tallow as a lubricant. Dry grinding invariably produces considerable heat and tends to leave a surface that is oxidized This, as soon as it becomes moist, usually discolors, taking on a yellowish brown tint.

All producers of stainless products usually exercise great care throughout all their operations to prevent iron contamination on the surface of the material. This same care should be used by the fabricator from the time the material arrives in his plant until it is delivered and installed in the customer's plant.

If iron contamination is known to be present or if the fabricator wishes to make sure that it is not, small parts can be immersed in a 15-20% solution of nitric acid at approximately 140°F. The parts should be rinsed clear of acid with hot water and then dried. This is generally termed "passivating." The iron is dissolved and the material assisted in building up its oxide-resisting surface. Large pieces of equipment can be filled with this acid or swabbed down several times, then rinsed clear of acid and dried. It should scarcely be necessary to caution that nitric acid is somewhat dangerous to use and that the operator should, therefore, be provided with eye protectors, rubber gloves and other protective equipment.

4. WELDING PROCEDURES

(a) Arc Welding of Stainless Steels

Austenitic Chrome Nickel Steels readily lend themselves to fabrication by means of welding. Of the various methods employed, metallic arc welding is by far the most widely used.

Coated electrodes are the rule and the welding is generally done with direct current using reversed polarity; that is, electrode positive and the work negative. Occasionally unusual conditions, particularly on heavy sections, indicate the use of straight polarity but because of the poor heat conductivity of these alloys very little heat is dissipated to the metal adjacent to the weld so that good penetration and less distortion are secured with reversed polarity.

The electrical resistance of this material is much higher than for mild steel and it is therefore recommended that the electrodes used be shorter than corresponding sizes of mild steel. The table which follows shows recommended electrode lengths and current values that should produce good results and a minimum of stub loss due to overheating.

Electrode Size, In.*	Length, In.	Amperage	Open Circuit Voltage†
3/32	9	35–80	35–40
1/8	11	60–100	40–45
5/32	12	80–150	45–50
3/16	14	105–165	55–60

* Electrode size usually equal to the sheet thickness with 3/16 in. max. for flat and 1/8 in. max. for vertical and overhead.
† Arc voltage 20–25.

The preparation of the joints to be welded is very important. All grease, paint or other foreign matter must be removed to prevent carbon pickup and inclusions in the deposited weld metal. Where long seams are to be welded it is important that the fit-up be accurate and suitable clamping or holding devices be provided to minimize warping. Where the long seams cannot be held in fixtures, "tacking" at short intervals will materially assist in preventing excessive warpage.

Fig. 6*a*—Square Edges for Plates 3/16 In. and Less

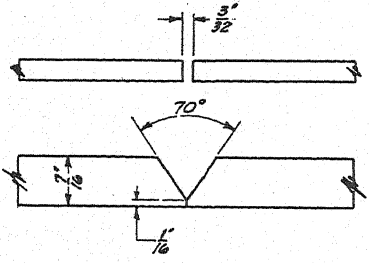


Fig. 6*b*—Groove for Plates 1/4 to 7/16 In.

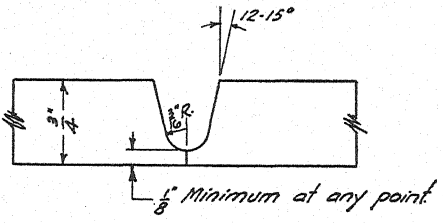


Fig. 6*c*—Groove for Plates 1/2 In. and Over

Butt Joint Design in Terms of Sheet or Plate Thickness (*t*)

	Up to 0.05 In.	0.05–3/16 In.	3/16–7/16 In.	1/2–3/4 In.		Above 3/4 In.	
Groove	Sq. Butt	Sq. Butt	Single V	Single V	Single U*	Double V	Double U*
Included angle	0	0	60–70°	60–70°	30°	60°	30°
Root face	*t*	*t*	1/16–3/32	3/32	1/8	1/8	1/8
Root opening	1/2*t*	1/2*t*	1/16–1/8	1/8	0	1/8–3/16	0
No. passes	1	1	Multiple	Multiple	Multiple	Multiple	Multiple

* U groove with 3/16-in. radius preferred for thicker sections because less cutting and less weld metal are required.

On plate material to secure proper fit-up and good welds it is necessary that the abutting edges be prepared by machining to provide a suitable groove for welding. On plate from 3/16 in. thick and less a square planed or sheared edge is generally used. On plate from 3/16 in. to 1/2 in. in thickness the edges are usually beveled and on thicker material the "U" type of groove is considered best. Figures 6*a*, *b* and *c* show the plate edge preparation details for the respective thickness ranges.

When several beads of welding are required it is advisable to use a number of light beads rather than to try to fill the groove in one or two passes because of the danger of shrinkage cracks and decreased corrosion resistance. Beading rather than weaving technique is desirable. Peening first layers is beneficial. Thorough cleaning with a blunt tool followed by a stainless steel brush should be applied before depositing successive beads. In all multiple pass welds, the root pass should be ground or chipped out from the back side down to clean, solid metal, after which the seal bead is deposited if the groove is single V or U, or alternate layer sequence is used between opposite sides of the double V or U groove.

The arc lengths should be maintained as short as possible to avoid excessive oxidation of certain elements in the electrode which would impair the corrosion resistance, and possibly the physical properties.

The quantities of weld material will vary slightly, dependent upon conditions, methods of welding and equipment. However, the table below will approximate closely the amount of filler metal per foot of joint that will be used to produce first class butt welds in these alloys.

Thickness, In.	Welding Time, Hr. per Ft.	Pounds of Filler Metal per Ft.
1/8	0.20	0.35
1/4	0.25	0.60
3/8	0.50	1.10
1/2	0.70	1.70
5/8	0.90	2.50
3/4	1.40	2.75
7/8	1.65	3.10
1	1.95	4.00

(b) Gas Welding of Stainless Steel

Suitability and Choice of Process.—The austenitic chromium-nickel steels can be welded successfully by both the oxyacetylene and the atomic-hydrogen processes. Oxyacetylene welding is particularly suitable for assembling light-gage parts which can be readily clamped in suitable jigs or fixtures.

Joint Design and Preparation.—Control of expansion and contraction on welding is more important with austenitic chromium-nickel steel than with carbon steel because the coefficient of expansion of the former is about 50% greater. It is achieved through the use of suitable jigs, fixtures and chill plates, by tack-welding, and sometimes by careful preheating. Suitable joint design facilitates this control and helps to avoid warping. See Figs. 7 to 11.

Stainless steel sheet, especially that under 0.04 in. (20 gage) is usually flanged before welding so that the length turned up is equal to the thickness of the sheet. Metal up to 1/16 in. (16 gage) can be satisfactorily welded with a butt type joint, while a veed joint is preferred for metal between 1/16 in. and 1/4 in. Above 1/4 in., the plate is preferably joined with double vees.

Unless highly polished, the stainless steel surfaces to be welded should be cleaned with fine sandpaper, or with other abrasive that is free from

every metal other than stainless steel. A special flux for oxyacetylene welding stainless steel is usually applied to the under side of the edges, and, in many cases, also is applied to the upper side.

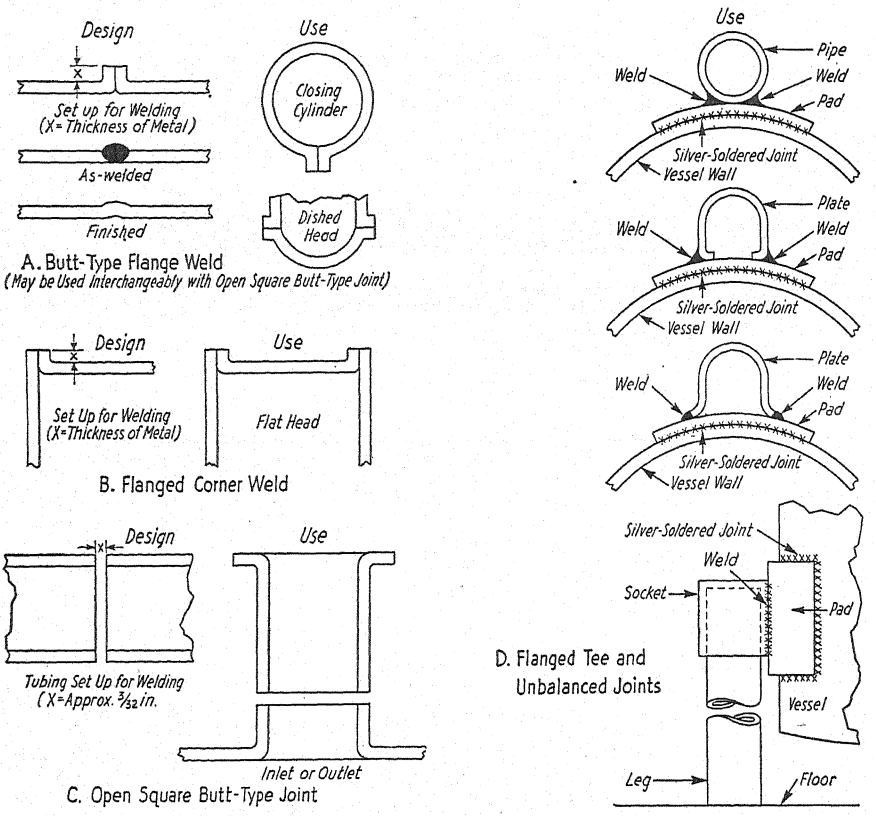


Fig. 7—Joint Design and Use

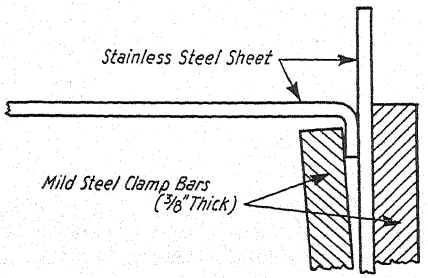


Fig. 8

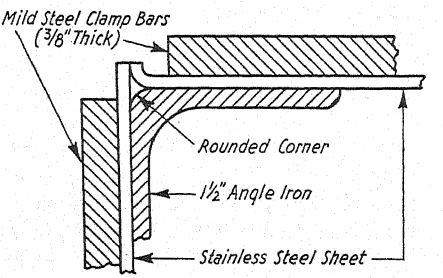


Fig. 9

Clamping Devices for Stainless Steel Welding

Oxyacetylene Welding Technique.—For austenitic chromium-nickel steel, the welding tip should be one or two sizes smaller than that used for ordinary steel, with the oxyacetylene flame adjusted just enough on the excess-acetylene side to eliminate the possibility of an oxidizing flame. With this adjustment the excess acetylene feather will not project more than $^1/_{16}$ in. beyond the tip of the inner cone, as seen through welding goggles.

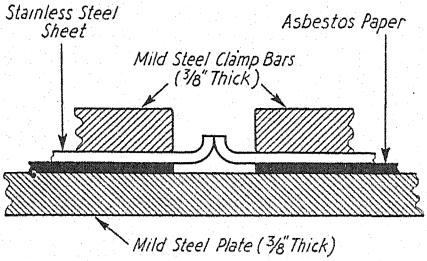


Fig. 10

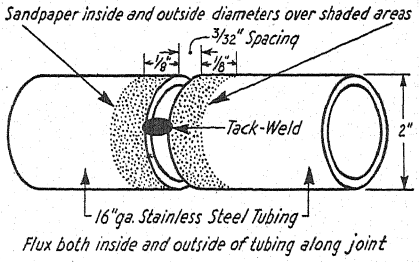


Fig. 11

The flame is generally held at an angle of 80° to the surface of the stainless steel, with the tip of the inner cone almost, but not quite, touching the molten metal.

Uniformity in welding speed is essential, the forehand method being preferred on light-gage sheet, while backhand welding on heavier gages is sometimes preferred when speed is important. Complete penetration should be obtained in one pass without puddling or retracing a weld. If, however, it is necessary to stop or to work over a weld, this should not be done until the weld has entirely cooled.

In the oxyacetylene welding of austenitic chromium-nickel steel castings, an excess acetylene flame is recommended.

(c) Automatic Welding of the Submerged Melt Type

The submerged melt process has been used successfully for welding some of the well-known chromium-nickel corrosion-resisting steels. The edge preparation for welding and the welding conditions are about the same for these materials as for plain carbon steels. For example, $^1/_2$-in. plate may be welded in a single pass using temporary copper backing and using a $^1/_4$-in. diameter welding rod with a current of 900 amperes, 38 volts, and a welding speed of about 15 to 18 in. per minute. The plate edges would be cut to form a single-vee preparation having 60° total angle with a $^3/_{16}$-in. root face at the bottom of the vee.

With submerged melt welding the molten weld metal is well protected from losses of the alloying elements in the steel. The following weld metal composition has been obtained in the welding of $^3/_4$-in. plate of A.I.S.I. Type 347 stainless steel using a welding rod of similar composition as the plate:

Carbon	0.07%	Nickel	10.61%
Manganese	0.30%	Columbium	0.84%
Silicon	0.97%	Nitrogen	0.043%
Chromium	18.27%		

An all-weld-metal tensile specimen had a yield strength (0.2% Set) of 40,700 psi. and ultimate strength of 76,500 psi. The elongation was 53% and reduction of area 56%. Izod impact test values were 55 ft-lb. where the notch was in the top portion of the weld and 56 ft-lb. where the notch was on the side of the weld. A free bend test showed an elongation of 40% with no failure.

A corrosion test specimen having 65% weld metal area was given the standard three period test in boiling 65% nitric acid.

The following are the results of the test:

	In Penetration per Month
1st period—44 hr.	0.00126
2nd period—47 hr.	0.00089
3rd period—42 hr.	0.00088

The corrosion rate in nitric acid is comparable with that obtained with rolled plate.

Experience indicates that chrome-nickel steels lend themselves quite readily to the submerged melt process of welding. Smooth uniform welds are obtained by practically the same procedure used in welding plain carbon steels.

(d) Atomic Hydrogen Welding

Atomic Hydrogen welding (see Chapter 7) is invaluable in the welding of light gages and produces an extremely smooth weld. However, because of the extreme intensity of the heat produced by this method of welding it is important that the work be suitably clamped and well tacked so that distortion will be minimized.

The type of work to be produced will generally indicate whether filler rods are needed. On light sheet and strip where the abutting edges can be bent up, this slight flange will usually provide the necessary welding metal. On heavier work it is customary to use bare wire of suitable analysis, generally the same as that of the base material for filler metal. This is used in a manner similar to that in which bare rods are used in other gas-welding processes.

Atomic hydrogen welding is widely used in the manufacture of heat exchangers where light gage tubes are to be welded to heavy tube sheets. In fact, for any welding operation where light gages are to be joined to heavy material this method will produce excellent results. It is also widely used in the welding of some of the more complex stainless alloys such as the Hastelloys.

The atomic-hydrogen process does not require the use of flux. Except for considerations of expansion and contraction, the welding technique for this process is essentially the same as for other steels.

(e) Resistance Welding

General.—In spot and seam welding of stainless steels the facts to be remembered are that due to the higher electrical resistance of chrome-nickel alloys the welding currents used are, in general, lower than those used for welding of mild steel and the pressures, for the same reason, consistently higher.

Because of the considerably lower heat conductivity the thermal gradient in the weld is considerably steeper than in case of mild steel welds with the result that the quality of the weld will be far more susceptible to the variation in the welding conditions such as magnitude and time of the welding current, the welding pressure, and the tip shape. This condition is further aggravated by the need of comparatively short welding time necessary because of the danger of carbide precipitation as explained later.

Successful spot welding of chrome-nickel alloys will then have the following requirements:

1. The magnitude of the welding current must remain the same at each weld and random transients cannot, therefore, be tolerated. In addition, it is preferable that the welding current remain uniform and as nearly sinusoidal as possible. For this reason the welding current should be applied always on the same point of the voltage wave, preferably the one which would not result in any transient current, and the voltage regulation at the welding transformer should not be more than 5%. The use of autotransformers between the welding transformer and the welding contactor should be avoided.

2. The duration of the welding current should be consistently the same. Welding at time intervals of less than 5 cycles ($^1/_{12}$ of a second) should not be attempted unless timing accuracy of better than $^1/_4$ of a cycle ($^1/_{240}$ of a second) can be assured. Whenever it is desirable to use very short time intervals as in the case of welding very thin metal gages, timing equipment of the full electronic type, independent of mechanical switching of current, should be used. A timing variation of more than 1 cycle ($^1/_{60}$ of a second) in the duration of the weld should not be tolerated in any case.

3. The welding pressure must be as uniform as possible, as any variation in pressure will affect both the current density of the weld (by changing the contact area) and the electrical resistance of the weld. For this reason, adequate jigs must be provided to hold the surfaces to be welded in good contact with each other and relieve the welding arms from the need of flattening out ripples and buckles.

4. The surfaces to be welded must be thoroughly cleaned and completely free from all scale, oxide, dirt, grease or drawing compound.

5. Considerably higher pressure should be used than is customary with mild steel. Very good results can be obtained with pressures two to three times those used on mild steel.

6. For best results the electrode tips should be made of special copper alloys possessing not less than 70 Rockwell scale B hardness, nor less than 85% electrical conductivity. They should be designed to operate at low temperatures, either by the use of water cooling or in some other way.

7. The lack of sufficient pressure manifests itself in the development of blow-holes inside the weld metal and, in extreme cases, in actual surface fusion of the metal. Proper pressure should be maintained at all times to ensure absence of both blow-holes and surface fusion.

8. Because of the comparatively high contact resistance of high-tensile austenitic steels, the short-circuiting effect of the preceding welds on each new weld may be considerable, particularly if more than three metal thicknesses are welded together at a time and if the spacing of spot welds is comparatively close. This effect should be measured and compensated for by a suitable increase of the welding current.

*Spot Welded Structures of High Tensile Stainless Steel.**—It has been established that with appropriate technique it is feasible to spot weld the high carbon (0.15% maximum) unstabilized material without harmful carbide precipitation and without undesirable loss of ductility in cold rolled material. High carbon (0.10–0.15%) is used for the high strength, cold rolled grades when maximum ductility for a given tensile strength is desired.

For the thinner gages of this material there is usually little difficulty in keeping the welding time below the danger point of harmful carbide precipitation, but in the thicker ranges the welding times and currents must be held much more closely within specified limits. In fact when the thickness much exceeds $^1/_8$ in. it is practically impossible, with available spot welding apparatus, to avoid undesirable carbide precipitation. Thus, if a structure made of this thicker material is to be subjected to a corrosive exposure, it is advisable to employ either the low carbon steel or stabilized steel according to the degree of such exposure.

It should be noted, however, that carbide precipitation such as might result from the spot welding of any of the standard steels in this group will not appreciably affect the physical properties of these steels until after they have been exposed to corrosive attack for a length of time depending upon the intensity of the corrosive agent. This time may vary from a few hours to a few months or even to a few years in the case of mild atmospheric exposure. Thus, it is entirely possible that even with what is commonly called low carbon 18–8 the carbide precipitation may be dangerous for certain corrosive exposures whereas if the exposure is completely non-corrosive, little danger will result from what is defined above as harmful carbide precipitation, as determined by the Strauss test, even in the case of the higher carbon steel.

However, since stainless steel is usually employed, in part at least, for its non-corrosive properties and since long time exposure in ordinary manufacturing atmosphere will result in intergranular corrosion of carbide precipitated material, it is not safe to assume that this material will be corrosion-resistant when spot welded by a haphazard or long time technique, particularly in the case of material with a thickness of 0.040 in. or more.

For these reasons the length of weld time used in welding of high tensile stainless steel of the type described above is of great importance if harmful carbide precipitation is to be avoided. In general the welding time must be of a comparatively brief duration and must be accurately controlled. The values of weld time given on Tables 5, 6 and 7 must not be exceeded in case of high tensile grades if harmful carbide precipitation is to be avoided.

However, with the use of proper technique as described herein the use of spot welding for high tensile, high ductility stainless steel of comparatively high carbon content is entirely satisfactory and, in fact,

* For mechanical and physical properties of various types of cold worked high tensile austenitic chrome nickel steels the reader is referred to the following articles:
"Stainless Steel," by J. M. Bandel, October 9, 1941 issue of "The Iron Age."
"Stress Strain Characteristics of Cold Rolled Austenitic Stainless Steels in Compression as Determined by the Cylinder Test Method," by Russell Franks and W. O. Binder, A.S.T.M., June 1941.
"Tension and Compression Stress Strain Characteristics of Cold Rolled Austenitic Chromium Nickel and Chromium Nickel Manganese Stainless Steels," by Russell Franks and W. O. Binder, Meeting of the Institute of Aeronautical Sciences, January 30, 1942.
"Tensile and Compressive Properties of Some Stainless Steel Sheets," by C. S. Aitchison, Walter Ramberg, L. B. Tuckerman and Herbert L. Whittemore, National Bureau of Standards—April 1942 issue of the National Bureau of Standards' Journal of Research.

Table 2—Spot-Weld Shear Strength

Thickness of Thinner Sheet, In.	Low Tensile 90,000–100,000 Psi.		Medium Tensile 125,000–150,000 Psi.		High Tensile 175,000–225,000 Psi.	
	Approx. Spot Diameter, In.	Shear Strength, Lb.	Approx. Spot Diameter, In.	Shear Strength, Lb.	Approx. Spot Diameter, In.	Shear Strength, Lb.
0.004	0.040	45	0.035	50	0.045	100
0.006	0.040	80	0.045	100	0.060	185
0.008	0.050	120	0.050	180	0.080	325
0.010	0.060	170	0.075	280	0.100	510
0.012	0.070	240	0.090	400	0.120	730
0.016	0.090	400	0.105	550	0.140	1000
0.020	0.110	620	0.120	750	0.155	1200
0.025	0.130	860	0.145	1,050	0.170	1450
0.030	0.150	1,100	0.160	1,300	0.190	1850
0.035	0.165	1,350	0.175	1,600	0.210	2250
0.040	0.180	1,600	0.190	1,850	0.230	2550
0.050	0.205	2,100	0.220	2,500	0.255	3250
0.055	0.220	2,400	0.235	2,800	0.265	3600
0.062	0.235	2,800	0.255	3,300	0.280	4100
0.072	0.260	3,400	0.28	4,000	0.310	4900
0.078	0.270	3,750	0.29	4,350	0.320	5300
0.081	0.280	3,950	0.300	4,600	0.330	5500
0.093	0.305	4,700	0.325	5,400	0.355	6500
0.109	0.330	5,600	0.36	6,600	0.40	7900
0.125	0.370	6,900	0.40	8,000	0.43	9400
0.157	0.430	9,500	0.48	11,900	...	...
0.187	0.500	12,300	...	...	...	...

Table 3—Spot-Welded Joint Design

Thickness of Thinner Sheet, In.	Low Tensile Steel 90,000–100,000 Psi. Range						
	Average Metal Strength per Inch at 95,000 Psi.	Single Row Spot Pitch, In.	Joint Eff., %	Spot Pitch In.	Distance Between Rows, In.	Joint Eff., %	Minimum Edge Distance, In.
0.004	380	3/32	95	3/16	3/32	100	3/32
0.006	570	1/8	95	1/4	1/8	100	3/32
0.008	760	1/8	95	1/4	1/8	100	3/32
0.010	950	5/32	95	1/4	1/8	100	1/8
0.012	1,150	3/16	95	1/4	3/16	100	5/32
0.016	1,520	3/16	95	3/8	1/4	100	5/32
0.020	1,900	1/4	95	1/2	1/4	100	3/16
0.025	2,380	1/4	95	1/2	1/4	100	3/16
0.030	2,850	5/16	95	5/8	5/16	100	3/16
0.035	3,325	5/16	95	5/8	5/16	100	1/4
0.040	3,800	3/8	90	5/8	3/8	100	1/4
.0050	4,750	1/2	85	5/8	3/8	100	5/16
0.055	5,225	1/2	80	11/16	3/8	100	5/16
0.062	5,900	5/8	70	3/4	7/16	100	3/8
0.072	6,850	11/16	70	7/8	7/16	100	3/8
0.078	7,410	11/16	65	7/8	1/2	100	7/16
0.081	7,700	3/4	65	15/16	1/2	100	7/16
0.093	8,750	3/4	65	1	1/2	100	7/16
0.109	10,350	13/16	60	1	9/16	100	1/2
0.125	11,900	7/8	60	1 1/8	5/8	95	1/2
0.157	14,900	1 1/8	50	1 1/4	3/4	95	5/8
0.187	17,800	1 3/8	45	1 3/8	7/8	90	5/8

this method of fabrication is probably the most practical for this type of chrome-nickel austenitic steel.

Spot Weld Cross Section Test.—A quick and fairly accurate method of checking the quality and strength of spot welds is by cutting a sample weld through the middle and, after a sufficient polish, etching it in a hot solution of 20% nitric and 5% hydrofluoric acid. The weld nugget will stand out in clear outline and the quality and approximate strength of the weld can be easily determined by measuring its diameter and depth of penetration. This method has the advantage of showing up the presence of any blow-holes or cracks indicative of insufficient welding pressure.

The appearance of the spot welds made on chrome-nickel steels is usually very good. By delaying the release of the welding pressure until the weld is cooled below oxidizing temperature, complete lack of discoloration can be obtained. If this is not practical, any discoloration present can be easily removed by pickling or washing in diluted sulphuric acid, or scrubbing with good alkali cleanser.

By using proper technique, complete lack of indentations on at least one side of the joint welded can be obtained.

Spot-Weld Strength.—The proper shear strength of spot welds is a function of the thickness of the sheet joined and to some extent of the purpose and the service of the joint. Tables 2 to 5 give the approximate weld diameter, spot shear strengths and recommended spot spacing for lap joints for fully stressed primary structures.

The spacing of spot welds joining stiffeners to panels, in reinforced panel designs is a function of the compressive load the panel is designed to carry without buckling between the spots.

The following formula can be used as a guide in determining the proper spot-weld spacing in terms of the buckling stress.

$$L = 1.8t\sqrt{\frac{E}{s} - \frac{E}{\text{T.S.}}}$$ (applicable only when weld is close to web of stiffener)

where

L = weld spacing
t = metal thickness
s = design stress at which buckling will appear in thinnest metal
T.S. = ultimate tensile strength of thinnest metal
E = Young's modulus of elasticity

Tables 6, 7 and 8 give approximate welding conditions required to obtain the spot welds of the recommended strength. So many factors enter into the formation of a weld that the figures given should be used as a very broad guide only, the exact conditions being determined for each grade of steel and each welding assembly.

The weld shear strength and to some extent the weld diameter should be used as a criterion for determining the exact welding condition. In addition, the weld metal should be free from blow-holes and porosity though on metal thickness 0.093 in. and thicker as well as on multilayer combinations exceeding $^3/_{16}$ in. in total thickness, a certain amount of porosity will be present unless extremely high pressures are used. It is generally agreed that in these cases a slight amount of porosity can be tolerated.

Table 4—Spot-Welded Joint Design

Thickness of Thinner Sheet, In.	Average Metal Strength per Inch at 137,500 Psi., Lb.	Single Row Spot Pitch, "A" In.	Medium Tensile Steel 125,000–150,000 Psi. Range: Joint Eff., %	Two Row Spot Pitch, In.	Distance Between Rows, In.	Joint Eff., %	Minimum Edge Distance, In.
0.004	550	3/32	95	3/16	3/32	100	3/32
0.006	825	3/32	95	3/16	1/8	100	3/32
0.008	1,100	1/8	95	1/4	1/8	100	3/32
0.010	1,375	3/16	95	1/4	1/8	100	1/8
0.012	1,650	3/16	95	3/8	3/16	100	5/32
0.016	2,200	3/16	95	3/8	1/4	100	5/32
0.020	2,750	7/32	95	3/8	1/4	100	3/16
0.025	3,440	1/4	95	1/2	1/4	100	3/16
0.030	4,130	9/32	95	1/2	5/16	100	3/16
0.035	4,810	5/16	90	1/2	5/16	100	1/4
0.040	5,500	3/8	80	1/2	3/8	100	1/4
0.050	6,870	1/2	65	9/16	3/8	100	5/16
0.055	7,560	1/2	65	5/8	3/8	100	3/8
0.062	8,530	5/8	55	5/8	1/2	100	3/8
0.072	9,900	11/16	50	11/16	91/2	100	7/16
0.078	10,700	11/16	50	11/16	91/2	100	7/16
0.081	11,100	3/4	45	3/4	/16	95	1/2
0.093	12,800	3/4	45	3/4	/16	95	1/2
0.109	15,000	13/16	45	13/16	5/8	95	1/2
0.125	17,200	7/8	45	7/8	11/16	95	9/16
0.157	21,600	1 1/8	40	1 1/8	3/4	85	5/8
0.187	25,800	...	...	...	...	...	...

Table 5—Spot-Welded Joint Design

Thickness of Thinner Sheet, In.	Average Metal Strength per Inch at 180,000 Psi., Lb.	Single Row Spot Pitch, "A" In.	High Tensile Steel 175,000–225,000 Psi. Range: Joint Eff., %	Two Row Spot Pitch, In.	Distance Between Rows, In.	Joint Eff., %	Minimum Edge Distance, In.
0.004	720	3/32	95	3/16	3/32	100	3/32
0.006	1,080	1/8	95	1/4	1/8	100	3/32
0.008	1,440	3/16	95	3/8	1/8	100	3/32
0.010	1,800	3/16	95	3/8	1/8	100	1/8
0.012	2,160	1/4	95	1/2	3/16	100	5/32
0.016	2,880	9/32	95	1/2	1/4	100	5/32
0.020	3,600	9/32	95	1/2	1/4	100	3/16
0.025	4,500	9/32	95	1/2	1/4	100	3/16
0.030	5,400	5/16	95	5/8	1/4	100	3/16
0.035	6,300	5/16	95	5/8	1/4	100	1/4
0.040	7,200	3/8	85	5/8	3/8	100	1/4
0.050	9,000	1/2	65	5/8	3/8	100	5/16
0.055	9,900	1/2	65	5/8	7/16	100	3/8
0.062	11,150	5/8	55	5/8	1/2	100	3/8
0.072	13,000	11/16	50	11/16	1/2	100	7/16
0.078	14,000	11/16	50	11/16	9/16	100	7/16
0.081	14,500	3/4	45	3/4	9/16	95	1/2
0.093	16,700	3/4	45	3/4	5/8	95	1/2
0.109	19,600	13/16	45	13/16	11/16	90	9/16
0.125	22,500	7/8	40	7/8	3/4	85	9/16

Frequently the geometry of the part welded is such that the pressures recommended in Tables 6 to 8 cannot be used. To some extent the lowering of pressure can be compensated for by decrease of current and increase of time. Any appreciable decrease of pressure, however, will result in a smaller and hence weaker weld, which in turn will lower the values given in Tables 2 to 5.

Distortion and Stresses Due to Spot-Welding Shrinkage.—The coefficient of expansion of the austenitic chrome-nickel steels is considerably higher than that of the mild or medium carbon steels. On the other hand, their

Table 6—Approximate Welding Conditions

	Low Tensile (90,000–100,000 Psi.) 18-8 Steel for Welding Two Metal Thicknesses				
Thickness of Thinner Sheet, In.	Electrode		Weld Pressure, Lb.	Weld Current, Amp.	Weld Time, Cycles
	Diam., In.	Dome Radius, In.			
0.006	5/8	1/16"—Flat—30°*	100	1,750	2
0.010	5/8	3/32"—Flat—30°*	175	3,100	2
0.016	5/8	1	278	4,750	3
0.020	5/8	1	350	5,700	4
0.030	5/8	2	500	7,200	4
0.040	5/8	4	750	8,400	5
0.050	5/8	4	1000	9,200	8
0.062	5/8	6	1300	10,000	8
0.072	3/4	6	1600	10,500	8
0.081	3/4	6	1850	11,000	12
0.093	3/4	6	2200	11,700	12
0.109	3/4	6	2500	12,600	15
0.125	1	8	3000	13,500	15
0.157	1	8	4300	14,700	20
0.187	1 1/4	10	5500	16,000	25

* Approach.

Table 7—Approximate Welding Conditions

	Medium Tensile (125,000–150,000 Psi.) Steel for Welding Two Metal Thicknesses				
Thickness of Thinner Sheet, In.	Electrode		Weld Pressure, Lb.	Weld Current, Amp.	Weld Time, Cycles
	Diam., In.	Dome Radius, In.			
0.006	5/8	1/16"—Flat—30°*	150	1,800	2
0.010	5/8	3/32"—Flat—30°*	250	3,400	2
0.016	5/8	1	350	4,600	4
0.020	5/8	1	450	5,200	4
0.030	5/8	2	650	6,600	4
0.040	5/8	4	825	7,400	5
0.050	5/8	4	1150	8,100	8
0.062	5/8	6	1500	8,900	8
0.072	3/4	6	1850	9,500	12
0.081	3/4	6	2100	9,900	12
0.093	3/4	6	2500	10,400	15
0.109	3/4	8	3000	11,300	15
0.125	1	8	3400	12,000	18
0.157	1	10	5000	13,800	20

* Approach.

thermal conductivity is much lower. Accordingly, it is to be expected that the distortion and stresses due to the actual welding shrinkage would be more severe in the case of the former than of the latter and that the opposite would be true with respect to warping and distortion due to the general or local heating of the structures incidental to the heat of the welding. The distortion, buckling and warping due to the shrinkage of spot- or seam-weld metal presents one of the most difficult and serious problems in welding and fabricating of stainless steels. In fact, it can be definitely stated that no welding of austenitic chrome-nickel structures should be attempted without first studying the effects of the shrinkage on the completed structure and making suitable provision for it in the design.

The extent of the welding shrinkage can be minimized to some extent in the case of arc welding by welding in short increments of 1 to 2 in. in length and staggering the increments through the length to be welded to balance out the net effect of the welding shrinkage. In some cases a very elaborate and carefully worked out sequence of welding must be followed.

In the case of spot or seam welding, the extent of welding shrinkage can be greatly reduced by keeping down the size of the individual spots. There is a very definite relationship between the stiffness of the sheets being welded and the amount of welding shrinkage within each individual spot which can exist without distorting the sheets. This relationship will vary, depending on the tensile characteristics of the sheets, but in general it will be found that the safe upper limit of spot-weld diameter is four to five times the thickness of the thinnest sheet welded. For this reason, from the point of view of shrinkage, more spots of smaller diameter are to be preferred to few spots of large diameter even if the total volume of weld metal is the same in both cases.

The distortion and warping produced by welding shrinkage can be overcome to a certain extent by peening or trip-hammering the weld metal.

Table 8—Approximate Welding Conditions

	High Tensile (175,000–225,000 Psi.), for Welding Two Metal Thicknesses				
Thickness of Thinner Sheet, In.	Electrode		Weld Pressure, Lb.	Weld Current, Amp.	Weld Time, Cycles
	Diam., In.	Dome Radius, In.			
0.004	5/8	1/16″—Flat—30°*	150	2,100	1
0.006	5/8	3/32″—Flat—30°*	300	2,400	2
0.008	5/8	1/8″—Flat—30°*	350	3,200	2
0.010	5/8	5/32″—Flat—30°*	400	4,000	2
0.012	5/8	2	450	4,700	3
0.016	5/8	2	500	5,250	4
0.020	5/8	2	600	5,700	5
0.030	5/8	4	750	6,700	6
0.040	5/8	4	1100	7,600	8
0.050	5/8	6	1500	8,100	8
0.062	5/8	6	1850	8,900	12
0.072	5/8	6	2250	9,200	12
0.078	5/8	6	2400	9,400	15
0.081	5/8	8	2600	9,500	15
0.093	5/8	8	2900	9,900	18
0.109	5/8	8	3400	10,800	20

* Approach.

As a rule it will be found helpful if all spot and seam welds are thoroughly trip-hammered, preferably one row at a time, at the end of each operation and before another welding operation is attempted.

(f) Joining of Austenitic Stainless Steels to Ferritic Steel

The welding of the austenitic stainless steels to mild ferritic steels can be readily accomplished by any of the accepted welding methods although for ease of operation and control, the metallic arc method is generally preferred.

Because the weld produced is of necessity a composite mixture of the two base materials and the welding rod used, proper consideration must be given to prevent the production of an air hardening and brittle weld which would crack upon cooling. The best preventive of this brittle condition is the use of a welding rod, whether gas or electrode, sufficiently high in alloy content that it will produce a weld having austenitic characteristics after dilution by the mild steel.

The most widely used material for this type of welding is either Type 309 (25–12) or Type 310 (25–20), the welding technique being the same as that used for any of the accepted welding methods and the same rules as to fit-up, electrode sizes and current values are applicable.

CHAPTER 20B

AUSTENITIC MANGANESE STEEL*

Effect of Heat, Welding, Contraction, Use of Stainless Steel Rods, Coatings to Facilitate Welding, Welding Technique, Welding Cracked Parts, Repairing Worn Surfaces, Welding Manganese Steel to Carbon Steel, Tests of Electrodes for Welding Manganese Steel.

AUSTENITIC manganese steel is used chiefly for parts subjected to heavy wear and stresses, such as steam shovel lips and teeth, stone crusher jaws or mantles, street and steam railway frogs, crossings and switches, etc. Welding of these parts is mostly for the purpose of restoring portions worn away, or repairing cracked or broken pieces. In addition, an increasing amount of work is being done in welding manganese steel castings or rolled material to other steels, for the purpose of protecting the rest of the assembly from concentrated heavy wear.

In welding this material, it is important to remember that besides containing some 12% manganese, it is intrinsically a high carbon metal, containing about the same amount of that element as the tool steel used for lathe tools. The average carbon of manganese steel is from 1.00 to 1.30%, but its great toughness in the heat-treated condition is so similar to that of structural plain carbon and low alloy steels that its different nature is often lost sight of by those attempting to weld it.

Effect of Heat

Without going too deeply into the subject, it may be advantageous to summarize here the facts about manganese steel and the effect of heat upon it, as follows:

1. Manganese steel before heat treatment is comparatively weak and brittle.
2. Manganese steel is made strong and tough by heating it to about 1900°F. and quenching it in water.
3. Toughened manganese steel is made weak and brittle by heating it to a dark red heat, or slightly below. The lowest red visible in the dark is 977°F. A temperature of 800°F. damages manganese steel. Water quenching from this temperature has no toughening or strengthening effect.
4. Toughened manganese steel, heated to temperatures between 800° and 1900°F. and then quenched in water, will have properties that depend upon

* Originally prepared by John Howe Hall, Consulting Metallurgist, Philadelphia, Pa., and revised by a committee consisting of B. H. Payne, Stulz-Sickles Co., and E. L. Quinn, American Manganese Steel Division, American Brake Shoe & Foundry Co.

the temperature to which it was heated. At lower temperatures it will be made brittle and weak. At temperatures approaching 1900°F. it will be made strong and tough.

5. Toughened manganese steel, heated to temperatures between 800° and 1900°F., or higher, and then allowed to cool slowly, is made weak and brittle; in this condition its structure corresponds more or less to that of the cast condition.

6. Toughened manganese steel that has been made weak and brittle by heating to incorrect temperatures below 1900°F. is fully re-toughened if heated to 1900°F. and quenched in water.

7. Manganese steel heated to over 2190°F. is permanently weakened. Water quenching from this temperature does not restore the toughness. A complete re-treatment following exposure to this very high temperature only partially restores its strength and toughness.

WELDING

Arc and Oxyacetylene.—To weld steel it must be brought to the melting point by some appropriate means. A shallow zone in manganese steel, therefore, must be brought to the weak condition described in (7) above. Another zone must be brought to the brittle condition described in (3) above. Neither of these zones is restored to toughness by immediate water quenching.

To heat only a portion of the part to 1900°F. and quench it leaves a zone somewhere that has been insufficiently heated, and hence is not made tough by quenching. Therefore, only complete re-heat treatment of the whole piece is effective, and even then there remains a partially damaged zone described in (7) above.

The foregoing explains the failure to secure consistently successful gas or arc welds by methods designed simply to keep manganese steel castings from excessive heat, such as immersing them in water, welding only at intervals, etc. These measures, to be sure, restrict the zone of damage and keep it close to the weld, but it is there. It is for this reason that welds in manganese steel have so often failed, and failed in such a way that the piece is in worse condition than before it was welded. The failure is generally in the manganese steel close to the weld, so that when the added metal comes off, it brings some of the piece with it, leaving a larger hole than the one welded up. Even when metal of exactly the same composition as that of the original part is deposited, the weld is apt to fail in this manner.

It is, of course, sometimes possible to make a welding repair on manganese steel in such a way that the weakened zone comes in a portion of the part heavier than the point of original failure, so that the unit stress in the damaged zone is at a minimum, and the weld as a whole will stand up. In general, however, it has been found by experience that to secure satisfactory results, welding materials must be used that partly counteract the harmful effects of heat described above. In particular, it has been shown that the presence of from 3 to 5% nickel in the deposited weld metal, coupled generally with a rather low carbon and a high manganese, results in greatly improved welds. The higher manganese, of course, is chiefly to offset the partial loss of manganese by oxidation that occurs in welding. The lower carbon serves to dilute the carbon of the partially fused zone, and

hence minimize its weakness, and the nickel has a similar, and probably more pronounced, effect. In addition, deposited metal of this composition does not require water quenching from a high temperature to keep the carbides in solution and make it tough and strong, as regular manganese steel does. A simple cooling in air from about 1800°F. is sufficient to make this material fully strong and tough. This is due to the absence of free carbides characteristic of the lower carbon material. As far as the deposited metal is concerned, therefore, water quenching is needless, and, as described above, it is not fully effective in toughening the zones of brittleness in the manganese steel close to the weld. It is recommended by practially all authorities, therefore, not to quench the welds in manganese steel, when nickel-manganese steel weld metal is used. In some cases the whole piece can be re-treated by bringing it to 1900°F. and quenching in water, but in the majority of cases the piece is put to work in the condition in which it leaves the welding operators hands.

Thermit welding of manganese steel parts has seldom been practiced because of the damage to the adjacent manganese steel by the heat of the thermit metal. A fairly successful weld might be made if the whole job were completely re-heat treated, but this of course is seldom possible.

Electric resistance welding of manganese steel parts has also not been used to any great extent, because of the difficulties that have been encountered in securing strong welds by this method.

Low-temperature stress relieving of a manganese steel part that has been welded, in order to eliminate the welding stresses, is obviously out of the question, in view of the harmful effect of low temperatures upon the steel, as described in (3) above. Careful experiments have proved that temperatures high enough to have any effect in relieving residual stresses destroy the strength and toughness of the original piece. The same thing, of course, is true in cases where a manganese steel piece is incorporated in an assembly by welding. However desirable a stress relieving treatment might be in such a job, it is out of the question to apply it, except in the exceedingly rare cases where the manganese steel portion need not be strong and tough.

The fact that manganese steel in the untreated or incorrectly heat-treated condition is comparatively weak and brittle, makes it next to impossible to secure strong welds in any but properly heat-treated manganese steel parts. It is occasionally necessary to completely re-heat treat the whole piece before a successful weld can be made in it. Welds should not be attempted at all in untreated castings.

A further obvious deduction from the foregoing is that in general gas welding of manganese steel parts is more apt to result in damage to the steel than arc welding. The metal is usually heated to a harmful temperature over a greater area, so that the strength and toughness of the base metal are reduced to a greater extent when welds are made with the gas torch. On all but very light sections that can be welded up rapidly and with a minimum of overheating, gas welding should not be attempted. As the harmful effect of the heat is chiefly due to temperature, and only to a slight extent to oxidizing conditions, special gas flames, such as that of the atomic hydrogen torch, are of little if any use as a palliative.

The same thing is true of the effect of coatings in reducing the harmful effects of either gas or arc welding on manganese steel. Since the damage is due so largely to temperature alone, and so little to contamination of the metal by atmospheric oxygen or nitrogen or other gases that may be present, a coating as a means of strengthening the weld is largely ineffective. It is of little use to generate a protective atmosphere to protect the weld from damage, when temperature alone is responsible for practically all of the damage done. The beneficial effect of coatings used to add special elements will be considered later.

Contraction

Manganese steel has a higher coefficient of thermal expansion than carbon or low alloy steels have. Hence the cooling stresses set up in a weld are greater in this material than in carbon steel. Unfortunately, too, manganese steel at temperatures just below its melting point is very weak and easily torn apart. This is especially true of metal deposited at the very high temperature of the arc or the gas flame, which has a much coarser crystalline structure than metal cast nearer its melting point. Therefore, if no steps are taken to counteract the effects of contraction as the job cools off, even a well-made weld in manganese steel will crack and tear in cooling. This is best taken care of by peening the weld metal severely as it cools, so that its contraction is offset by the expansion due to the peening. Peening should be continued until the metal is black. An air hammer, if available, is best; if no air is at hand, a machinist's hammer should be employed, and the deposited metal pounded vigorously until it has cooled off. Generally the best practice is to peen the deposited metal immediately as each length of rod is used up. Some operators prefer to peen after using half a rod. In this way, cracks can be prevented from occurring, whereas if a longer interval is allowed to elapse before peening is begun, more or less cracking will take place. Peening should begin at the end of the bead that was deposited first to allow the crater time to solidify before it is peened.

Use of Stainless Steel Rods

It was formerly quite common practice to use "18–8" welding rods (18% chromium—8% nickel) to weld cracks in manganese steel parts, or to weld pieces together, covering the weld over with manganese steel to provide a good wearing surface. Indeed, some concerns still advocate this practice and claim that it is not possible to secure strong welds with manganese or nickel-manganese steel rods. Hadfields Limited—the firm of Sir Robert Hadfield, inventor of manganese steel—do not agree with this claim. In his annual report to the shareholders for 1935, Sir Robert Hadfield stated that his firm had abandoned the use of 18–8 rod for this purpose, because they found they secured stronger welds with nickel-manganese steel rod.

The following figures, collected over a six-year period, give the results of bending tests on arc welds in cast manganese steel test bars made with several different makes of nickel-manganese steel electrodes, and with 18–8 electrodes.

Size Test	Weld Rod	No. of Tests	Bend		
			Avg.	High	Low
3/4 in. square	Ni-Mn	189	65°	106°	30°
3/4 in. square	18–8	6	16°	30°	9°

The corresponding figures for tensile tests are less numerous, but tell the same story. They are as follows:

Electrode	No. of Tests	Tensile Strength, Psi.		
		Avg.	High	Low
Ni-Mn	16	55,900	71,400	40,000
18–8	2	28,400	38,700	18,100

Elongation in 2 in. on four of the above tests made with nickel-manganese steel electrodes averaged 8%. With 18–8, an elongation of 3% was secured. Unwelded bars average about 90,000 psi. tensile strength and 20% elongation.

Twist tests of 3/4-in. square bars of cast manganese steel, unwelded, broke at 2 3/4 and 3 1/4 complete twists. Bars arc welded with nickel-manganese electrodes endured 1 1/2 turns without breaking in one case, and broke at 1 3/4 turns in another.

Tests on gas welds made by a representative concern gave the following figures on bars 2 1/2 × 1/2 × 5 in. welded with nickel-manganese steel rods:

Condition	Tensile Strength, Psi.	Angle of Bend, Deg.
As welded	62,000 to 68,000	18 to 25
Re-heat treated	43,000 to 76,000	26 to 45

One-inch square cast manganese steel bars gas welded, without reheat treatment, bent from 8° to 12°.

The best proof of the reliability of welds in manganese steel, of course, is the success that has been attained in service. Properly made welds in manganese steel stand up for long periods. Several of the steam railroads give three years as the life of repairs to manganese steel trackwork with nickel-manganese steel rod. There are cases on record where cracked and broken steam shovel fronts welded with this material have lasted through two seasons' work in a limestone quarry, and many other similar instances could be cited.

The strength of the weld, of course, depends chiefly upon the presence of the correct amount of carbon, manganese and nickel, uniformly distributed throughout the deposited metal. These alloys, therefore, need not be incorporated in the body of the electrode, but may be added by mixing them in a coating. Indeed, one might even say they could be added with a salt shaker, provided the proper amount could be introduced, as, of course, it could not. In this case, the rapid diffusion of the alloys at the high temperature of the molten metal is depended upon to give a deposit

of uniform analysis. That this diffusion takes place to a satisfactory extent is indicated by the fact that there are electrodes on the market and in successful use, in which the carbon and alloys are contained at least in part in the coating.

Coatings to Facilitate Welding

In addition to their function as carriers of the alloys, coatings such as those just described are intended to give a steady arc and to protect the deposited metal from oxidation. Coatings are also often applied to the alloy steel electrodes for the same purpose. With a coated electrode it is easier to hold a steady arc, the metal bubbles much less, and it is not necessary to take the same care to allow gases to escape from the deposited metal. A thinner layer of metal can be laid down than is possible with the bare alloy electrode, and alternating current can be used with coated electrode, but not with bare electrodes. These advantages would appear to be sufficient to make it almost essential that coatings be applied to nickel-manganese steel electrodes. Aside from their cost, however, there is one pronounced objection to some of the coatings that have been, and still are, applied to these electrodes, and that is that they tend to weaken the welds made with them. In some cases this is due to the incorporation of materials in the coating that increase rather than decrease the loss of manganese by oxidation, in some cases to the addition of undesirable elements such as excess carbon and in other cases to causes not quite clear. The material used for coatings in these cases is usually satisfactory as far as quieting the arc and making a smooth-flowing rod are concerned, but is of such a nature that it has a harmful effect upon the strength and toughness of the weld metal. When testing coated electrodes for welding manganese steel, therefore, it pays to try the electrode both with and without its coating. This, of course, does not apply in the case of the electrodes in which the coating is used also as a vehicle for the introduction of the alloys.

Welding Technique

In arc welding with nickel-manganese steel electrodes, reversed polarity should be used—that is, the electrode should be the positive pole. With bare electrode, the arc is quite lively and sputters rather violently, and the deposited metal boils freely. If the arc be moved steadily forward, therefore, time will not be allowed for the escape of the gases from the metal, and a porous deposit will result, as shown at *2* in Fig. 1. To overcome this difficulty the arc should be moved in a figure 8 from left to right as it is advanced, so as to keep the deposited metal molten and "puddle" it long enough to allow the gas to escape. This, of course, gives a wider bead (about $\frac{1}{2}$ to $\frac{3}{4}$ in. wide), but a sound one. Such a bead is illustrated in *3*, Fig. 1. That bead, however, has a "crater" at the point where welding ceased, because the arc was broken abruptly. To prevent this the arc should be made and broken several times at this point, even burying the rod momentarily in the pool. A bead so laid down is shown at *4* in Fig. 1.

As already described, a nickel-manganese steel electrode with a suitable coating welds more smoothly, the arc sputters hardly at all, and it is possible to move the end of the electrode steadily along without puddling the pool of

metal. Indeed, some of the coated electrodes of this metal are self-feeding; the arc once started the electrode can be laid flat upon the work and the arc will travel steadily up the electrode, like a slow-burning fuse, laying down a sound deposit. The slag coating over the deposited metal should break off readily at a light blow of the hammer, so that peening is not delayed by the time taken to chip off the slag. With properly coated electrodes, peening can be started almost immediately as each length of electrode is used up, as in the use of the bare electrode

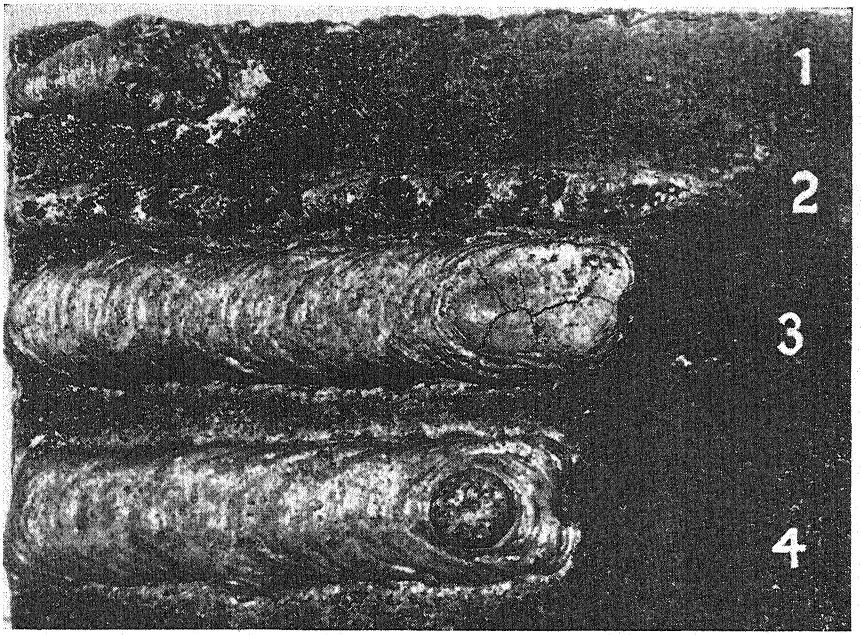


Fig. 1

No. 1—Weld made without reversing polarity. Has no penetration.
No. 2—Weld made without lateral movement of electrode. Full of gas pockets.
No. 3—Weld correctly made, but cracks at end result from failure to peen or fill up crater.
No. 4—Weld correctly made and crater filled.

In general, it is best to lay the beads of each layer at right angles to those of the layer below, or at least at as high an angle as is feasible. In laying on metal to rebuild worn surfaces this is generally easy to accomplish. In repairing cracked or broken castings, especially heavy ones, the high angle may not always be easy to secure.

The current usually recommended for nickel-manganese steel electrodes is as follows:

Diameter Rod	Bare Electrodes D.C. Amperes	Coated Electrodes D.C. Amperes	Coated Electrodes A.C. Amperes
1/8 in.	80–100	85–105	90–110
5/32 in.	90–125	95–130	100–135
3/16 in.	110–150	115–155	120–160
1/4 in.	135–160	140–170	145–175

Work should be properly grounded.

For gas welding a tip should be selected large enough to melt down the metal with a soft flame, in order to minimize bubbling of the metal. A neutral flame should be used; a carbonizing flame injures the strength of the weld by raising the carbon of the deposited metal. Though a carbonizing flame makes the metal flow more freely, its use should be avoided.

WELDING CRACKED PARTS

In the repairing of cracked or broken castings or forgings of manganese steel, it is essential that welding should be started only upon sound, homogeneous metal. When unsound or heavily rusted metal is present on the surface to be welded, therefore, it must be removed before attempting to start the weld. In an effort to minimize the amount of heat applied to the job, it was formerly the practice with many welding operators to insist that this part of the work be done entirely by the slow, tedious and expensive method of grinding. Since much heating of the metal is inseparable from the welding operation, the value of this precaution was more theoretical than useful, and it has largely been superseded by cutting with the gas torch. Properly handled, a torch will cut away the defective metal with but slight heating of the part. In fact, in cutting manganese steel parts with the torch, the effect of the heat in changing the structure has been found to extend as a rule to a depth of less than $1/4$ in. There is very little if any alteration of the composition of the steel as a result of the use of the cutting flame, except in an exceedingly thin surface layer, and of course the heat of welding will extend considerably beyond the shallow zone in which the cutting flame has changed the structure. Obviously, therefore, the bulk of the work of cutting out porous or oxidized metal can be done with the torch, and the wheel used simply to finish up the task. In fact, it is not absolutely essential that the wheel be employed at all, as good welds can be made if the cut surfaces are welded just as they are left by the torch.

Cracks should be cut out to the bottom, and the sides should be cut back to a liberal V so that the electrode can be handled freely. Cracks extending completely through a part must of course be cut out all the way through. Whether to use a single V notch, so that the welding is started at one side and continued until the space is filled up, or to use a double V, welding first from one side, then from the other, is to some extent a matter of personal choice. It would appear, however, that when a double V is used, the metal first laid down is apt to crack when the piece is turned over and welding is begun on the other side. The heat from the second stage of the job expands the whole piece, setting up severe stresses in the completed portion of the weld that may result in a visible tear, or what is worse, a hidden one. When using a single V, on the other hand, if the layers are carefully peened as they are laid down, it is possible to neutralize the stresses to a large extent by expanding the deposited weld metal with the peening hammer.

To a certain extent the same thing is true of welding a part that is completely broken in two, or welding one piece of manganese steel to another, but in many cases the rule cannot be adhered to literally. In welding new ends to worn-out dipper teeth, for instance, the thickness of the sections makes it essential for reasons of economy that the weld metal be applied from both sides.

Cracks extending in from the edges of a piece should preferably be welded first at the closed end of the crack, leaving the sides free to expand and contract. As the weld at the closed end is built up, the weld is carried further toward the open end in a "step" effect, the lowest step in each case being that nearest the open end. By the time the closed end of the crack in a heavy piece is completely filled up, therefore, the weld has been extended a considerable distance toward the open end, growing thinner in regular stages until the last step is but one layer thick. This method, of course, is adopted in order to allow the open end of the crack to expand and contract freely as welding proceeds. If an attempt is made to lay down first a single layer the full length of the crack, then a second layer upon the first, and so on, the expansion of the piece from the heat of the successive layers is apt to crack the weld metal near the open end of the crack before the job is completed.

REPAIRING WORN SURFACES

Much of the work in welding manganese steel is in rebuilding worn surfaces to the original contour. One of the most common jobs of this type is the repair of steam and electric railway special trackwork. The recommendations of the National Transit Society for work of this type embody the principles set forth in the foregoing pages with certain additional precautions that are especially applicable to trackwork.

These castings being commonly rather thin, their capacity for the absorption of heat without becoming very hot is naturally limited. It is especially important, therefore, to use the lowest amperage or heat that can be employed and still secure good fusion and penetration. Otherwise the work may grow too hot with resulting damage to the strength of the parent metal. For the same reason it is recommended that welding be carried on intermittently at different points on the casting, welding only when the bare hand can be held on the work 6 in. from the weld.

It is suggested further that the ends of all seams be tapered so that the continuation of the weld will form an overlap at least long enough to fully cover the crater. Start the second bead somewhere near the middle of the first bead, staggering similar to breaking joints when laying bricks. When welds are made on rail ends, frog points, etc., they should be applied so as to make the finished weld terminate diagonally across the rail or casting, rather than straight across or at right angles to the rail. Lay beads, particularly the first layer, longitudinally with the rail or length of castings. Never weld a bead across the head of the rail at right angles to it.

The floors and risers on frogs in electric railway trackwork should generally be welded and finished first. Finish all welds thoroughly by grinding smoothly.

Apply sufficient metal to produce a surface and alignment when ground and finished that will meet the adjacent unwelded material on a uniform surface and alignment. Grind all gage lines and frog points sufficiently to remove all short points and edges.

The above suggested methods apply equally to most work in building up worn castings, with of course modifications in the exact order of laying

down beads, shaping the ends of the welded areas, etc., that can only be determined by the nature of the job in each case. When a considerable amount of metal is to be deposited upon a worn part, however, it is frequently found desirable to utilize manganese steel or nickel manganese steel bars or cast pieces of suitable shape and build them into the body of the weld in order to save time, current and welding rod. These repair bars are obtainable from several sources.

In the case of steam and electric railway trackwork, however, such a method is generally inapplicable because it is desirable to maintain the special work by building it up as often as it has worn down a small amount, say $^3/_8$ in., rather than let it become very badly worn so that a heavy layer has to be laid down. Welding in this case is best used as a means of maintenance rather than a method of repairing wornout parts.

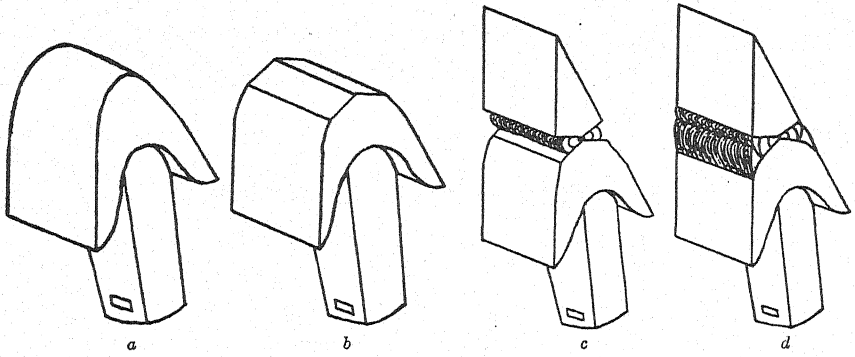


Fig. 2—Rebuilding Dipper Teeth

The worn tooth (*a*) should be beveled as in (*b*). Short heavy beads should be used as in (*c*) and continued until a smooth surface is obtained between the filler bar and the tooth face.

When a considerable amount of metal is to be deposited on a worn part, it is frequently found desirable to utilize cast manganese steel, or manganese nickel steel bars or cast pieces of suitable shape and build them into the body of the weld in order to save time, current, and electrodes. One of the best known and most frequently used applications of the special cast manganese bars is the repointing of worn down power shovel teeth of manganese steel. These bars are of a wedge shape cross section or of a diamond shape cross section with one point longer than the other. A piece of sufficient length to suit the width of the tooth to be rebuilt is cut off with the torch and placed with the blunt end toward the job, the longer end forming the new digger point. The roughly V shape space between the tooth and the repair point is then filled in with metal, the finished job being of the same general shape as the original tooth, Fig. 2. Another well-known application is the use of manganese nickel steel rolled bars in flats, rounds, squares and special shapes. These bars are used largely for building up worn surfaces as jaw, gyratory, cone and roll crushers and the special shape bars are used largely for replacing worn down grousers on tractor treads and for replacing clam shell bucket lips. There is inevitably considerable damage done to the toughness and strength of the manganese steel parent metal when doing this work, but the zone of maximum damage comes in

the heaviest part of the parent metal so that the harmful effect of loss of strength is minimized. A welder utilizing his spare time is able to keep these parts in repair at a cost that makes it an economical operation.

WELDING MANGANESE STEEL TO CARBON STEEL

When manganese steel is to be welded to carbon or low alloy steels, the strength of the job depends greatly upon the nature of the steel to which the manganese steel is to be attached. Nickel-manganese steel weld metal will adhere well to soft and medium soft steels, especially when a suitably coated electrode is employed. In this way a wearing face of weld metal can be laid down on a carbon steel part, or a special piece of manganese steel to resist wear can be attached by seam welding. If the manganese steel part be set in a recess, the production of a strong job is very easy, and, even when no such precaution is taken, a reliable weld can be counted on. On hard steels such as are more commonly used for steam railroad rails, however, the strength of the bond between the nickel manganese steel weld deposit and the hard steel is low. Such welds can seldom be counted upon to stand up in service. In these cases the use of special materials for the first layer of weld metal on the hard steel is resorted to. In a patent upon this method of welding granted to A. R. Welch,[1] the use of a low carbon, 5% nickel steel electrode is recommended. It has been found that a comparatively strong weld between manganese steel and hard rail steel can be secured by this method. The 5% nickel steel is first laid against the hard steel, and the space remaining between this first layer and the manganese steel part is then filled in with nickel-manganese steel electrodes.

TESTS OF ELECTRODES FOR WELDING MANGANESE STEEL

The National Transit Society has adopted regulations for testing electrodes for welding manganese steel that embody the use of the so-called "free bend" test of a welded bar. Two pieces, 2 in. wide, $1/2$ in. thick and 4 in. long of rolled or cast-manganese steel, are welded together under the procedure recommended by the manufacturer of the electrodes, and tested in the manner recommended for free bends by the AMERICAN WELDING SOCIETY. The elongation secured on the outside of the bend is specified to be at least 7%. A nick-break test is also recommended, the fractured surface to show complete penetration through the entire thickness of the weld, absence of harmful oxide or slag inclusions, and a degree of porosity not to exceed six gas pockets per square inch in the total area of the weld surface exposed in the fracture. The maximum dimensions of any such pockets are not to be in excess of $1/16$ in.

Drillings for chemical analysis from a pad at least $3/4$ in. thick, deposited at one end of the bar used for the nick-break test, must show a manganese content of at least 11%, according to this specification.

[1] U. S. Patent 2,060,765.

In making welds of these test bars, and similar small parts that are to be welded together, it is not feasible to peen the deposited metal at intervals. In fact, as the recently deposited weld metal is rather weak, to attempt to peen it would simply result in breaking the two pieces apart. In such cases it will be found most satisfactory to simply build the weld up in successive layers, trying not to heat too much of the manganese steel close to the weld, and using the hammer only to knock off the slag when using coated rod. Indeed, the peening in such cases is obviously not necessary, as the parts, being small and light, are free to move as they expand and contract, and excessive stresses in the weld are not to be expected.

CHAPTER 21

CAST STEEL AND GRAY AND MALLEABLE CAST IRON*

Cast Steel—Classification, Specifications, Weldability, Preheating Requirements, Technique, Heat Treatment, Physical Properties; Cast Iron—Gas Welding, Metal Arc Hot and Cold Welding, Carbon Arc Welding, Thermit Welding, Bronze Welding, Welding with Non-Ferrous Nickel-Copper Electrodes, Metallurgical Factors, Microstructural Factors, Physical Properties; Malleable Cast Iron—Methods of Welding, Metallurgy, Physical Properties, Pearlitic Malleable.

A. CAST STEEL

Classification

STEEL castings may be classified into five general groups, as follows:

1. Low carbon steels (carbon less than 0.20%).
2. Medium carbon steels (carbon between 0.20% and 0.50%).
3. High carbon steels (carbon content above 0.50%).
4. Low alloy steels (alloy content less than 8%).
5. High alloy steels (alloy content greater than 8%).

Carbon content maximum in steel castings may be arbitrarily fixed at 1.7% for purposes of definition. In the bulk of steel castings produced the carbon content will lie in the range 0.20 to 0.50%. In the alloy steel castings the general compositions will follow rather closely the compositions of the similar wrought steels.

All of the cast steels may be welded with suitable welding technique, practice being the same as for wrought steels of similar grade. For general constructional welding the carbon content in the straight carbon steels should be kept below 0.30%; steels with higher carbon require special

* Prepared by a committee consisting of A. J. Smith, The Lunkenheimer Co., *Chairman;* T. N. Armstrong, The International Nickel Co; J. W. Bolton, The Lunkenheimer Co.; C. W. Briggs, Steel Founders Society of America; C. H. Jennings, Westinghouse Elec. and Mfg. Co.; G. F. Landgraf, Lebanon Steel Foundry; G. A. Ross, General Electric Co.; G. S. Schaller, University of Washington; H. A. Schwartz, National Malleable and Steel Castings Co.; J. S. Vanick, The International Nickel Co.

handling to avoid embrittlement. Specifications have been drawn recommending certain steels as suitable for fusion welding and close attention should be paid to them. These are included in the following section.

Specifications

Under the various code specifications repair welding is permitted on steel castings of all analyses covered. The consent of the purchaser's inspector is required for repair welding in practically all cases. With entry of castings into welded structures specifications have been drawn covering steels suitable for this purpose. The applicable specification should be consulted for details.

In general the A.S.M.E. Boiler Construction Code and A.S.A. Standards duplicate, with certain exceptions, the A.S.T.M. Standards for similar material. The U. S. Government specifications are scattered through many publications and are more concerned with quality of weld than with the materials to be welded. The U. S. Navy Department, however, lists certain steels, titles of which appear below.

The standards follow with their code numbers, together with various notes appearing in the specifications governing repair welding.

1. "Carbon Steel Castings for Miscellaneous Industrial Uses." A.S.T.M. A27–39; A.S.M.E. Boiler Code No. S-11.

2. "Carbon Steel and Alloy Steel Castings for Railroads." A.S.T.M. A87–36.

3. "Carbon Steel Castings Suitable for Fusion Welding for Miscellaneous Industrial Uses." A.S.T.M. A215–41T.

4. "Carbon Steel Castings for Valves, Flanges and Fittings for High Temperature Service." A.S.T.M. A95–41. All castings after welding must be reheat-treated, except castings with minor welds with the permission of the inspector need not be reheat-treated.

5. "Carbon Steel Castings Suitable for Fusion Welding for Service at Temperatures up to 850°F." A.S.T.M. A216–41T; A.S.M.E. Boiler Code No. S-56; A.S.A. No. B16e-39. Major repair welds: "When the removal of a defect necessitates a major repair weld, repair shall be at the discretion of the purchaser's inspector. The repair weld shall be made by an approved process after the inspector has been permitted to examine the casting with the defect removed. All castings with major repair welds shall be reheat-treated. When required by the purchaser, major repair welds shall be radiographed at the manufacturer's expense to check the adequacy of the repair."

6. "Alloy Steel Castings for Structural Purposes." A.S.T.M. A148–36.

7. "Alloy Steel Castings for Valves, Flanges and Fittings for Service at Temperatures from 750 to 1100°F." A.S.T.M. A157–41; A.S.M.E. Boiler Code No. S-33. For repair welding see No. 5.

8. "Alloy Steel Castings Suitable for Fusion Welding for Service at Temperatures from 750 to 1100°F." A.S.T.M. A217–41T; A.S.M.E. Boiler Code No. S-57; A.S.A. No. B16e-39. For repair welding see No. 5.

9. "Austenitic Manganese Steel Castings." A.S.T.M. A128–33.

10. "Chromium Alloy Steel Castings." A.S.T.M. A221–39. Repairs may be made by welding with either electric arc or oxyacetylene process. With the electric method, a flux coated rod is to be used, except in the case of the atomic hydrogen process, when a bare metal rod may be satisfactorily employed. When the oxyacetylene method is employed, care must be exercised to so control the operation that carbon absorption does not occur. All castings shall be reheat-treated after welding.

11. "20% Chromium, 9% Nickel Alloy Steel Castings." A.S.T.M. A198–

39. Deposited weld metal must have corrosion resistance equivalent to that of base metal. Reheat treatment after welding required.

12. "Chromium Nickel Alloy Steel Castings." A.S.T.M. A222-39. For repair welding see No. 10.

13. "Nickel Chromium Alloy Steel Castings." A.S.T.M. A223-39. For repair welding see No. 10.

14. "Steel, Corrosion Resisting: Castings." U. S. Navy 46 S27. Material must be examined for carbides prior to welding. Not to be repaired without consent. Welding rod of same composition to be used.

15. "Steel Castings." U. S. Navy 49 S1-K also 49S1-(INT).

16. "Steel, Alloy, Molybdenum: Castings." U. S. Navy 46 S33.

Specifications for constructional welding of cast parts are, in general, the same as for the welding of similar classes of wrought materials.

Effect of Manufacturing Variables on Weldability

Steel castings may be made by any of the melting processes used in the production of wrought steels. Within the normal compositions of the welding grades of steel castings, it is the consensus of opinion that steel-making processes are not a factor in weldability considerations.

General Weldability and Preheating Requirements

For discussion of the metallurgy involved in the welding of cast steel, see Chapters 2 and 3. The cast and wrought steels are similar in most respects, although a somewhat better structural stability at times has been found in steel castings. Steel castings having a carbon content higher than 0.30% often require preheating; those with less than 0.30% carbon seldom require preheating.

The purpose of preheating is to retard the cooling rate and only enough preheat should be given to fulfill this purpose. Excessive preheating temperature leads to excessive coarsening of structure. For cast carbon steels of welding grade a preheating range of 200 to 400°F. is adequate even under severe conditions. For the low alloy steels somewhat higher preheating temperatures may be necessary. Knowledge of the effects of the different alloys will serve as a guide for preheating; naturally steels of oil and air-hardening grades require more preheat than less sensitive materials.

Since the high alloy steel castings are very similar to wrought parts of equivalent composition, discussion of the welding of these steels will be found in Chapter 19 on Chromium Irons and Steels, and in Chapter 20 on Austenitic Steels to which the reader is referred.

Welding Technique

For general considerations of technique of welding, refer to Chapters 4 to 13, inclusive.

As in welding wrought materials, the procedure should be qualified as outlined in the A.W.S. Standard Qualification Procedure.

In general, the welding of castings may be divided into two groups; namely (1) the fabrication of either one casting to another or to wrought material and (2) the repair of defects. In the first case, a groove prepara-

tion can be made to conform to general practice used in welding wrought materials, and in the second case, the groove preparation will be governed largely by the extent of the defect.

One of the prime requisites for making a satisfactory repair weld is the complete removal of all defective material. In the preparation of the area to be welded proper side-wall bevel should be provided and the root so planned as to secure complete penetration. If the defect lies at considerable depth it is usually preferable to provide an open root for the weld if this is consistent with the casting design.

For major repair welding both radiographic and magnetic testing are advocated both before and after repair. The U. S. Navy Department has defined the extent to which repairs of castings for steam pressure service are permitted in its "Gamma Ray Radiographic Standards of the Bureau of Engineering for Steel Castings for Steam Pressure Service." Reference to these standards will clearly indicate the application of the radiographic testing method and the limits of repair welding. They are a useful guide for repair welding of all classes of castings.

Filler Metals and Coatings

Welding rods used for welding steel castings are the same as for wrought steels of similar composition. Reference may be made to the corresponding sections on wrought steels for full details on this subject.

Heat Treatment

Welded steel castings may be heat treated for two purposes: (1) to remove residual stress acquired during welding, and (2) to improve the metallurgical and mechanical properties of the weld, heat affected area and the casting proper.

1. Stress Relief Heat Treatment.—The relief of stresses in welded cast steels is accomplished by following the practice commonly used for wrought steels. Stress-relieving temperatures of 1100 to 1200°F. are satisfactory for nearly all castings with the possible exception of the heat-resisting grades. Occasionally annealing temperatures are used to obtain desired metallurgical changes. Practices of this type may be considered under the class of heat treating for metallurgical effects.

The normal soaking time employed with the stress-relieving treatment is one hour plus one hour per inch of thickness. This soaking time may be increased with the higher alloy castings but it should not be reduced.

The object of heat-treating for stress relief is to remove residual stresses. Care must be taken to insure constant temperature throughout the section at the stress-relieving temperature in order to avoid thermal stresses that may remain permanently after cooling. Cooling from the stress-relieving temperature should be at such a rate that no new transient thermal stresses are set up which would vitiate the effect of the relief anneal.

Many codes contain specifications for stress relieving and in cases where such a code applies the requirements contained therein should be followed.

2. Heat Treating for Metallurgical Effects.—Since the metallurgical reactions of cast steels are essentially the same as those for wrought

materials, it is recommended that the appropriate sections of the following chapters be referred to:

Carbon Steel Castings—refer to Chapter 17.
Low Alloy Steel Castings—refer to Chapter 18.
Chromium Iron and Steel Castings—refer to Chapter 19.
Austenitic Steel Castings—refer to Chapter 20.

Physical Properties of Welded Joints in Cast Steel

The physical properties of welded joints in cast steels depend on the compositions of the castings, the types of filler metal used and the welding processes. The filler metal used is the same as that used for wrought materials, consequently for a given analysis of base metal the physical properties will be essentially the same whether the base material is cast or wrought.

1. Carbon Steels.—Most carbon steel castings are repaired with arc welding using coated electrodes, although occasionally bare electrodes or carbon arc welding is used. Welds made with coated electrodes have superior physical properties and are generally recommended.

Carbon steel castings are generally welded with low carbon or low alloy filler metal similar to the carbon-molybdenum variety. The physical properties obtained will depend upon the particular type of filler metal used and the dilution obtained from the fused parent metal. When making large welds the effect of dilution should not be relied upon to improve the tensile properties of the welds. The principal reason for using low alloy filler metal when welding plain carbon steel castings is to obtain tensile properties higher than can be obtained with low carbon filler metal.

Typical physical properties of arc-welded joints in steel castings are as follows:

	Low Carbon Bare Electrodes	Low Carbon Coated Electrodes
Yield point, psi.	35–40,000	50–55,000
Tensile strength, psi.	50–60,000	60–70,000
Elongation, % in 2 in.	5–12	18–28
Reduction of area	8–18	30–60

2. Low Alloy Steels.—Typical physical properties of arc-welded joints in low alloy castings are as follows:

	As-Welded	Stress Relieved
Carbon-molybdenum castings welded with filler metal of similar composition:		
Yield point, psi.	65,000	52,000
Tensile strength, psi.	75,000	70,000
Elongation, %	20	30
2% Nickel castings with filler metal of similar composition:		
Yield point, psi.	70,000	55,000
Tensile strength, psi.	85,000	70,000
Elongation, %	20	30
Chrome-manganese-silicon castings welded with filler metal of similar composition:		
Yield point, psi.	85,000	80,000
Tensile strength, psi.	95,000	90,000
Elongation, %	18	20

5% Chromium - molybdenum castings welded with austenitic stainless steel electrodes:		
Yield point, psi.	75,000	70,000
Tensile strength, psi.	85,000	80,000
Elongation, %	20	25

Low alloy steel castings may be used for two purposes: (1) to obtain certain physical properties at room temperatures and (2) to obtain certain physical properties at high and low temperatures—for example, high creep strength at high temperatures and high impact strength at low temperatures. When welding castings of this type it is important to know what the service requirements are because many times it is essential that the weld have approximately the same chemical and physical characteristics as the base metal.

3. High Alloy Steels.—High alloy steel castings are generally welded with electrodes having a similar analysis. The physical properties obtained in such cases compare very closely to those of the parent metal.

B. CAST IRON

Introduction

Cast iron is characterized by high carbon content, the major portion of which exists in the form of graphite flakes. The carbon content in most commercial cast iron will range between 2.50 and 3.70%, although some of the high-strength irons now produced may have slightly less carbon than 2.5%. Silicon also is present in commercial irons within the range 0.50 to 3.00%. The matrix structure may vary all the way from ferrite, with all the carbon graphitic, to pearlite.

Most of the iron produced today, including the high-strength gray iron, is of pearlitic matrix. The combined carbon in the pearlite is readily broken down at temperatures above about 1300°F. to graphite and ferrite with a consequent loss of strength and to the accompaniment of some volume change. Reabsorption of the carbon at temperatures near the melting point offsets this decomposition making it possible to secure high-strength welds in cast iron. If the iron is low in carbon or silicon, or both, cementite is formed on rapid cooling forming chill or hard spots. Beyond these factors there are few differences to be found structurally between the welding of cast iron and steel welding, the melting temperatures of cast iron being considerably lower, of course.

General volume expansion and contraction must be considered in welding of cast iron because of the low ductility of the material. By the use of suitable preheating a combined operation of stress relieving and avoidance of chill is obtained.

Gas Welding

The welding of cast iron is almost always performed by gas welding, using the oxyacetylene flame and a cast-iron filler rod.

Preheating.—The main purpose of preheating in the gas welding of cast iron is to insure a soft weld deposit in which the combined carbon is low

and to avoid a hardened fusion zone. Another important purpose is to prevent the accumulation of stresses of excessive magnitude during the welding process. Most authorities recommend preheating to a temperature of about 1000°F.

Type of Flame.—A neutral flame is generally employed although a slightly carburizing flame is sometimes advantageous, as, for example, when there is a deficiency of carbon. For alloy cast-iron rods essentially the same technique applies as for plain cast-iron rods. Care should be taken to avoid overheating because, in general, the alloy rods are much more fluid when melted.

Technique of Gas Welding.—The crack is chipped out to form a 75–90° vee. Rust must not be allowed to form in the vee. A little flux is spread over the starting point and the flame played on the vee until the walls begin to melt. The metal of the outer walls of the vee should not melt ahead of the metal at the root, otherwise there is no fusion at the root. The rod, dipped in flux, is then brought to a red heat and rubbed into the molten metal. The molten metal should never be dropped into the puddle if slag inclusions are to be avoided, nor should a cold welding rod be plunged into the molten metal if hard spots are to be avoided. When the surface of the metal appears dirty a small quantity of flux should be added. It is generally agreed that the tip of the blue cone of the flame should be kept from $^3/_{16}$ to $^7/_8$ in. away from the molten puddle to avoid hard spots and loss of silicon and carbon. Sand specks cause blow-holes if they are not brought to the surface.

Fluxes.—Early in the history of gas welding it was found necessary to use fluxes for cast iron. A great number of flux compositions have been suggested. The action of aluminum powder is said to be in the nature of a Thermit reaction. The powder, when scattered on the red-hot metal, gives rise to incandescence, the metal becoming fluid, and blow-holes are prevented. The presence of aluminum in the flux also prevents loss of silicon. A flux that is frequently mentioned contains sodium carbonate and bicarbonate; a typical example is 15% borax, 15% sodium carbonate and 60% sodium bicarbonate.

Low Temperature Brazing with Low Melting Point Cast-Iron Filler Rod.—Low temperature filler rod is now available with which it is not necessary to bring the base material to a fusion temperature. The casting is prepared as for fusion welding and the joint brought to a temperature at which the filler metal flows freely and wets the joint. A cast-iron weld rod of low melting point is used as a filler material. Special fluxes are used as in normal cast-iron welding. Usually a slightly reducing flame is recommended.

Filler Rods for Gas Welding.—For plain cast-iron welding rods of the following composition are recommended, C, 3.2–3.7%; Si, 2.75–3.5%; Mn, 0.5–0.75%; S, 0.1%; P, 0.5–0.7%. Uncoated rods are generally used, but flux coated rods are now available.

Low alloy cast-iron welding rods are available for general purpose welding containing appreciable quantities of alloys such as Ni, Mo, Cr, Cu, V, etc. These rods, in general, produce cast-iron welds stronger and denser than those made with plain rods. In some cases special alloy cast-iron filler rods are available in compositions to match castings of special analysis.

High alloy rods are available to match such special analyses, as, for example, Ni-resist (a corrosion-resisting high nickel austenitic cast iron),

and in this case the weld deposit retains the properties of the parent metal. These high alloy rods can also be used for overlaying plain cast-iron castings to obtain the advantages of the special analysis in the overlaid coating at low cost.

Metal Arc Welding

Both ferrous and non-ferrous electrodes are used to electric weld cast iron which may or may not be preheated. Non-ferrous electrodes (see "Welding with Non-Ferrous Nickel-Copper Electrodes") may be used without preheat to yield machinable deposits, essentially free of hard white iron, where, in contrast, deposits made with ferrous electrodes under the same conditions usually contain hard white iron. Regardless of the electrode used (ferrous or non-ferrous), a narrow martensitic (hard) zone is formed in the unfused parent metal, when no preheat is used, due to the heat effect of welding. Therefore, where machinability requirements are rigid, this hard zone in the casting must be prevented by a mild preheat of 500°F.

Hot Arc Welding

1. Preheating.—The preheating of cast iron has the purpose of decelerating the cooling rate thus reducing thermal stress and producing a machinable weld.

2. Technique.—The hot welding process (so-called) can be used in a manner very similar to and in application like that of gas welding.

3. Electrodes. (*a*) *Cast Iron.*—Cast-iron electrodes are used for the so-called hot welding by the metal arc process. The composition of the electrode is similar to that used in gas welding. Amount of current depends upon the size of the electrode and the mass of the casting, and in this respect is similar to that required for the arc welding of steel. The electrodes are normally coated with protective flux, but are often used bare. With bare or lightly coated cast-iron electrodes, a preheat of about 1000°F. is required. Some electrodes of special cast iron are manufactured, for which claims are made that machinable welds can be produced with a preheating temperature as low as 300°F. Welds made with these electrodes should show good strength properties without loss of machinability.

(*b*) *Bronze Welding.*—See Bronze Welding or Brazing.

(*c*) *Nickel-Copper.*—See "Welding with Non-Ferrous Nickel-Copper Electrodes."

Cold Welding Process

Ferrous or non-ferrous electrodes may be used for the so-called cold welding. As mentioned above, the non-ferrous electrode may occasionally be used to obtain machinable deposits. Cold welding with ferrous filler rods is used for welds that need not be machined and that are not too thick. It is usually employed in connection with studs.

Technique.—The technique of cold welding has been developed to offset the tendency of cast iron to crack when locally heated. The general principle involved in all cold welding is to build up the sides of the joint with a steel electrode before closing the joint itself with steel weld metal. The

ductile mild steel can then yield under the contraction stresses imposed by the joining beads. The cast iron is built up by depositing curved beads or by welding intermittently. In both systems, cleaning or chipping away oxidized metal and slag is essential, and peening is desirable. Cold welding uses as little heat as possible and is essentially a multi-layer process, but the annealing effect of multi-layers is not sufficient to prevent the formation of hard zones. See also "Welding Cast Iron with Non-Ferrous Nickel-Copper Electrodes."

Electrodes.—Mild steel covered electrodes are generally used in the cold process. The composition of the core of the electrode is seldom mentioned as important. The coating of the electrode may perform two functions: (1) it may shield the arc and weld metal (shielded arc or flux covered electrodes); (2) it may alloy with the steel core to produce a cast-iron deposit. The coating for the first purpose is apparently of the same nature as on ordinary mild steel covered electrodes, and is designed to avoid nitrides. Carbonaceous coatings are used for the second purpose. One authority has found a coating of 40 to 60% graphite, 1% barium carbonate and the rest carborundum, with a paste of water glass as a binder, to be particularly effective.

The amperage used for covered electrodes in cold welding is kept low in order to reduce heat, hardening and cracking. For example a $^1/_8$-in. electrode on $^1/_2$-in. material using 80–90 amp. is a common value. See also "Welding Cast Iron with Non-Ferrous Nickel-Copper Electrodes."

Carbon Arc Welding

The technique of carbon arc welding closely resembles that of hot metal arc welding. Preheating from 200 to 1300°F. is used together with annealing or slow cooling. Graphite rods are generally used and a flux containing equal parts sodium carbonate and sodium bicarbonate is useful. Filler rods are generally the same as for gas welding.

Thermit Welding

In the Thermit process a sand mold is built around the chipped or machined fracture and the parts are preheated. Molten metal is then poured into the mold. Thermit suitable for cast iron is plain Thermit (a mixture of finely divided iron oxide and aluminum) to which 3% ferrosilicon and 20% mild steel punchings are added. See Chapter 13.

Bronze Welding

Preheating.—Preheating, although not always necessary, is usually applied to assure success. The preheating may be local or general depending on the casting. A black preheat is generally employed although in some cases preheating to 1650°F. has been found advantageous.

Technique.—As pointed out by the International Acetylene Association, if the temperature of the base metal in bronze welding is too low, the bronze does not spread out; if it is too high the bronze collects in little balls which are driven away by the force of the flame. To avoid overheating, the torch should be held at a smaller angle to the deposited metal than in

welding with cast iron rod, according to one authority. Bronze welding of large joints should be done in several layers. The removal of graphite from the surfaces to be welded has always been considered important. Graphite may be removed by scaling the surface at 1650°F. or by use of an oxidizing flame.

Type of Flame.—A slightly oxidizing flame is usually recommended.

Fluxes.—The flux should be oxidizing in character in order to remove graphite, and it should remove oxide films from the base metal, otherwise capillary flow of the bronze (tinning) will not occur without overheating.

Filler Rods.—The customary filler rod for bronze welding is a brass containing 60 Cu, 40 Zn. If the zinc content is too low the hot strength is correspondingly low; if zinc is too high the deposited metal is too hard and brittle. Tin, iron, manganese and silicon, about 1%, are often added to improve the flowing characteristics, decrease fumes, deoxidize and increase the hardness.

Types of Joint.—The vee need be only wide enough so that the torch can be inserted. Double vee joints are used for thick sections. In pipe welding the shear vee* joint is recommended.

Metallurgy.—The bond is developed by intergranular penetration of brazing metal along graphite flakes or grain boundaries, by solid solution formation and by tinning. Graphite, especially flake graphite, causes poor adhesion. There is considerable evidence to show that brazing metal penetrates the cavities left by oxidized graphite flakes.

Physical Properties.—In discussing the physical properties of bronze welds it must be remembered that the bronze deposit generally has a tensile strength of from two to three times the tensile strength of the fusion contact and in many cases a strength greatly in excess of the cast iron itself. The shear strength of the junction zone is about 25,000 psi. and the tensile strength about 35,000 psi. In order to bring up the strength of the welded joint the shear vee butt joint and elongated or shear fillets are resorted to. This gives greater area of fusion contact. The junction zone is not any more brittle than the cast iron itself.

Welding Cast Iron with Non-Ferrous Nickel-Copper Electrodes

Nickel-copper electrodes may be used with or without preheat to weld cast iron. In either case, the *weld deposit* will be readily machinable. In welding without preheat, however, the cast iron will exhibit a martensitic structure in a narrow zone adjacent to the weld, an effect which, of course, is independent of the type of electrode used. When necessary, this hard zone can be avoided by the use of a 500°F. preheat.

In most instances heavily coated electrodes are used although some welding is also done with electrodes having only a thin wash coating, deposits made with the latter generally being more inclined to exhibit porosity.

Preheating.—This is a matter which must rest to some extent on the judgment of the operator, who must consider the type of weld to be made, the type of casting to be welded and the requirements to be met by the welded casting.

* A vee joint the upper part of which is considerably widened to secure larger contact area.

For simple welding operations involving the filling in of casting defects in castings of moderate to heavy sections, arc welding is readily accomplished without preheat and the deposit is machinable. Where a joint is involved, such as in repairing a cracked casting, particularly one where pressure tightness is involved, a 500° preheat should be used to reduce thermal stresses and thus minimize cracking tendencies of the weld and of the casting.

In castings of rigid design, especially those of light section, if no preheat is used, the casting may crack during welding in an area remote from the weld due to thermal stresses set up in cooling, although an entirely satisfactory weld may have been obtained. Also, in all types of castings, when machinability requirements are severe, and the presence of a hard martensitic zone in the unwelded cast iron immediately adjacent to the weld is not permissible, a 500° preheat is indicated.

Welding with Preheat.—The castings should be preheated to desired temperature (about 500°F.) and not permitted to go appreciably below the preheat temperature during welding.

With non-ferrous electrodes narrow beads should be laid in about $2^1/_2$ in. long using reversed polarity. For $^1/_8$-in. diameter electrode use 90 to 100 amp., and for $^5/_{32}$-in. use 120 to 130 amp. As soon as the arc is broken the deposited weld metal should be peened.

If wide, heavy beads are laid down in one pass, excessive shrinkage stresses are set up, with subsequent cracking. Therefore, narrow beads are recommended.

After deposition of the first bead, succeeding narrow overlapping beads should be laid into the vee, until the weld has been completed; then on the other side of the vee, and finally these beads should be joined with a single pass through the center. This is to prevent the shrinkage of the weld metal clear across the vee which results nearly always in cracking.

After welding, the entire casting should be permitted to cool slowly from the preheating temperature.

Welding Without Preheat.—To prevent high stresses developing in the casting as a result of welding and to minimize cracking of the casting, steep temperature gradients are to be avoided, i.e., the heat resulting from electric welding should be spread as widely as possible to avoid localized hot spots.

The weld metal should be laid in narrow beads using proper polarity and just sufficient current to obtain fusion of the base metal. Non-ferrous electrodes $^1/_8$ in. and $^5/_{32}$ in. in diameter are recommended. Larger electrodes should not be used. A bead of about $2^1/_2$ in. in length should be laid down followed immediately by peening.

Upon completion of 2 in. to 3 in. length of bead and after peening, the casting and weld should be allowed to cool to finger warmth (so that the hand can be laid on the area just welded), before depositing another short length of bead 2 in. to 3 in. long. While one weld is cooling down, a second casting, or another weld in the same casting can be electric welded.

Electrodes.—Most of the non-ferrous electrodes (available from a number of sources) comprise either: (*a*) a nickel-copper core (such as Monel) with a suitable flux coating; or (*b*) a composite electrode containing a nickel core, sheathed with copper (or copper and iron), suitably flux coated.

Metallurgical Factors

Oxidation of Iron.—Since the melting point of cast iron is about 390°F. below the melting point of FeO, molten cast iron at temperatures below about 2375°F. is covered with a solid oxide film. If the solid oxide is intermingled with the molten cast iron, it is difficult to remove. Early adoption of fluxes to make the slag fluid, and of puddling, the end of the filler rod being held below the slag, shows that oxidation of iron was one of the first difficulties overcome in welding cast iron.

Composition of Casting.—The chemical composition of cast iron to be welded is a major factor in welding. Low-silicon cast iron, with its small graphite flakes, is easier to weld than high-silicon because large graphite flakes do not provide a clear foundation for the weld. Cast iron containing over 0.9 to 1.5% Mn or over 1.8% Si is difficult to weld by any process, whereas welding is facilitated if the casting contains nickel, titanium or vanadium.

Microstructural Factors

Hard Spots.—There is unanimous agreement that the hard, unmachinable zones generally found in cold welds and in improperly executed hot welds consist of white or nearly white cast iron. Invariably the hard zones contain not merely excess cementite but ledeburitic or eutectic cementite, suggesting that the composition or rate of cooling has been unfavorable to the precipitation of graphite during or immediately subsequent to solidification.

Graphite Structure.—An examination of the microstructure of all welds in cast iron, with the possible exception of burn-on welds shows that the graphite structure in the weld is finer than that of base metal. At times it is possible to observe a thin layer of altered "grown" graphite in the junction zone at the boundary to which weld metal had penetrated, which seriously lowers the transverse strength. However, the graphite layer is in no sense an unavoidable defect in cast-iron welds.

Heat Treatment.—It is common practice to anneal some cast-iron welds after welding for three reasons: (1) to remove shrinkage stresses, (2) to break down hard spots, (3) to decrease carbon gradient. Heat treatment at 1400°F. followed by water quenching has been known to improve the strength of gas welds beyond that of unwelded cast iron without decrease of cross-bend deflection.

Physical Properties

A good gas weld made in cast iron has approximately the same strength as the cast iron being welded. The same is true for arc welding (preheated). Cold arc welds made with either cast iron or mild steel are quite variable. Preheated gas and arc welds have approximately the same ductility as cast iron. Cold arc welds made with cast-iron or steel electrodes are definitely inferior in ductility.

Impact.—Arc and gas welds preheated and annealed have practically the same value as the cast iron.

Fatigue.—Gas-welded specimens give about 90% of the endurance limit of unwelded cast iron.

Repeated Impact.—Unannealed gas welds under repeated impact withstood approximately 40 times as many blows as unwelded specimens. Annealing reduced the number of blows withstood by the welds to approximately the same as that of the cast iron.

Welding Cast Iron to Other Metals

With special precautions gas (with cast iron or bronze), arc and resistance welding may be successfully used in joining mild steel to cast iron.

MALLEABLE CAST IRON

The malleable cast iron in common use in this country is "black-heart" malleable cast iron (0.6–1.1 Si, up to 0.4 Mn, under 0.20 P, 0.06–0.15 S). Since the physical properties are dependent on certain heat treatments (malleableizing) which it undergoes, the heat of fusion welding, as may be expected, will permanently change the structure and physical properties unless the temperature is kept low (1380°F. as will be noted later).

Methods of Welding

Bronze welding has therefore become the usual method of repair. The method is the same as for gray cast iron. The edges to be welded are beveled to 90° and cleaned. The scarfs should not be ground; grinding is said to bring graphite to the surface and to make tinning difficult. The casting is then preheated to a black heat (locally for small castings) and bronze welded using a tip one size larger than for similar work on steel, and an oxidizing flame. Flux is used liberally. The rod may contain 59 Cu, 40 Zn, 1 Sn or 1 Fe plus some Mn; lead is bad. Other rods such as manganese bronze and Cu-Zn-Si high strength brass have also been found to be successful.

If the casting may be re-annealed, that is, malleableized after welding, either arc or gas welding may be used.

The best procedure for black-heart is to use oxyacetylene welding on the preheated casting whether hard or annealed, employing a white cast-iron filler rod. Re-annealing is necessary and the weld then has a structure similar to the casting, but finer grained. For (decarburized) sections up to nearly $1/4$ in. thick the castings can be welded like cast steel, using borax and mild steel filler rod. Decarburized sections thin enough to permit this practice are, however, so unusual as to make this practice of little importance commercially. Above $1/4$ in. the same procedure as for gray cast iron is used. Plenty of borax and a high-silicon rod are employed. After being welded, the castings are heated rapidly to 1400 to 1480°F., held $1/2$ to 1 hr., and cooled slowly in sand. This treatment, however, does not produce a weld identical with the original casting. Pearlite always remains and with very high-silicon rod primary graphite may be found in the welds. Up to 0.3 in. thick white-heart castings need not be re-annealed.

Black-heart may be welded with steel electrodes in the same way as gray cast iron, but annealing after welding is essential. Such annealing always leaves a pearlitic zone which, if machining is not intended, is un-

objectionable. Special coated small diameter electrodes using low current are recommended.

It has been suggested that white-heart castings may be annealed 30 min. at 1650–1750°F.; black-heart 2 hr. at 1650°F. (packed in sand) for best results after welding, except for simple small or thin castings for which annealing is unnecessary. Double annealing is of no value. These treatments do not appear, however, to have any successful practical application and are not recommended.

Monel metal electrodes or other nickel-alloy rods are recommended to weld small defects and build up unfinished surfaces when the malleable casting must be machined after welding.

White castings may be resistance welded prior to malleableizing. White cast iron is easily oxyacetylene welded using white cast-iron rods of the same composition as the casting. Bevels are ground or flame cut and the casting slightly preheated.

Metal arc and oxyacetylene welding are: (1) to repair cracked white castings; (2) to fill in surface imperfections of annealed castings (a more common practice than No. 1). In both cases welding is followed by the usual annealing cycle, and the welding rod is usually white cast iron of the same composition as the original casting. The welds are almost indistinguishable from base metal after malleableizing. Alloy malleable cast iron is said to behave substantially the same as unalloyed in welding, although some analyses may give difficulty.

Metallurgy

The weldability of white- and black-heart malleable cast iron by metal arc and resistance butt processes increases with decrease of total carbon, silicon, phosphorus, sulphur, gases and inclusions, and increases with manganese up to 0.5%, weldability being measured by physical properties.

Micrographs of specimens of white-heart and black-heart heated to fusion on one end and fitted with thermocouples along the heat gradient show that the hard zone forms at 1910°F. in white-heart and at 1740°F. in black-heart. These temperatures are indicative of the degree of superheating to which the metal can be subjected *very briefly*. Actually if the temperature be maintained for any considerable time the maximum which may be reached without recombination of carbon is but little in excess of 1400°F. as noted in the next paragraph. Micrographs also show the impossibility of avoiding the hard zone in malleable cast-iron welds, except bronze welds, short of reannealing.

The maximum temperature to which black-heart malleable may be heated by the torch in bronze welding is 1420°F. above which a hard layer is produced.

In this country 1290 to 1400°F. is regarded as the critical point or maximum temperature to which a malleable casting may be momentarily heated without embrittlement by pearlite formation.

Physical Properties

The tensile strength and elongation of good arc, gas and resistance welds

in malleable cast iron which have been malleableized after welding are approximately 90% of those of the original malleable cast iron.

Pearlitic Malleable

Pearlitic malleable is the trade name of a material similar in character to malleable iron, but whose metallic matrix intentionally contains significant amounts of combined carbon. The term is not very happily chosen for this combined carbon is not necessarily present in the form of pearlite. Metal of this character can, in general, be welded using soft steel or even intermediate carbon steel welding rod. Such welds if held for an hour or so at a temperature just below the critical point are so far softened as not to differ greatly in properties from the metallic matrix. Annealing treatments which raise the metal above its critical point are, however, not permissible since they alter the matrix structure which is essential to produce the properties of the parent metal.

CHAPTER 22

COPPER AND COPPER ALLOYS*

Copper Alloy Base Metals, Copper Alloys as Filler Rods and Brazing Metals, Important Alloying Elements, Effect of Added Elements, Welding Procedures for Copper and the Various Alloys by Groups.

COPPER enters into the composition of several hundred commercial alloys[1] sold under more than a thousand different names. It is possible, however, to arrange the alloys, important in welding and brazing operations, into a comparatively small number of groups, the metals in each group having somewhat similar metallurgical and welding characteristics. This has been done for the copper alloy base metals in Table 1. Only those alloys having 40% or more of copper are included in this chapter. Other alloys in which copper occurs as an important constituent are found in the chapters on Fundamentals of Welding Metallurgy, Chapter 2, Part 3, Low Alloy Steels, Chapter 18, Nickel Alloys, Chapter 24, Brazing Alloys, Chapter 14A, Silver Brazing Alloys, Chapter 14B, Copper Brazing Alloys, Chapter 14D, and Bronze Surfacing, Chapter 15-B.

Owing to the fact that some of the copper alloys have been proved particularly valuable as welding rods or weld metals, a separate classification, Table 2, is made to show a convenient grouping of such alloys and their properties of interest in welding.

Table 3 shows the appropriate welding method and welding rod in Table 2 applicable to any copper alloy base metal of Table 1.

The three tables are followed by a discussion of the copper alloys group by group with detailed notes on the effect of the significant welding properties of the various elements and the recommended welding procedures.

COPPER ALLOY BASE METALS

The alloys grouped in Table 1 for ready reference are used as sheets, plates, rods, tubes, wire and, in some cases, as extruded shapes, forgings and castings. The more common commercial names of the various alloys are

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given in the caption for each group while the accepted uses of the metals are sketched briefly in the remarks following the tabulation of properties. Only those properties of primary interest in metals which are to be welded are given. Since in each group the composition varies over wide limits, the values given for the different properties are necessarily only approximate.

Table 1.—The entire copper alloy field has been separated into eleven different groups designated by the numbers of column 1. From the standpoint of certain general characteristics, copper and deoxidized copper are

Table 1—Copper Alloy Base Metals

Group No.	Composition,* %	Average Tensile Strength, Psi. Soft	Hard Δ	Elongation in 2 In., % Soft	Melting Point °F.	°C.	Conductivity Elec. % I.A.C.S. 20° C.	Thermal π
1A.	Copper, tough pitch copper, electrolytic copper, Lake copper:							
	99.9 Copper, Minimum 0.03 to 0.07 Oxygen as Cuprous Oxide	32,000	40,000 to 67,000	35	1981	1083	100	0.92
	The usual copper of commerce. Sheet, wire, extruded or drawn shapes. Electrical or high conductivity copper.							
1B.	Deoxidized copper:							
	0 to 0.05 Phosphorus 0 to 0.10 Silicon Rem. Copper	35,000	40,000 to 67,000	35	1981	1083	80 ±	0.80 ±
	Commonly deoxidized with 0.01 to 0.05% phosphorus or 0.03 to 0.10% silicon. Calcium boride, calcium-lithium or silicon used where high residual electrical conductivity is desired. Copper tubes for all purposes, sheets for welding, gas welding rod, high conductivity castings.							
2A.	Gilding 5 to 10% zinc, commercial bronze 10 to 12% zinc, red brass, rich low brass 15% zinc; red brass, low brass 20% zinc; zinc bronze with zinc and tin; red brass castings, ounce metal, hydraulic bronze with zinc, tin, lead and copper:							
	5 to 20 Zinc 0 to 8 Lead 0 to 6 Tin Rem. Copper	30,000 to 40,000	50,000 to 95,000	35 to 20	1949 to 1832	1065 to 1000	55 ΔΔ to 15	0.58 ΔΔ to 0.20
	Sheets, tubes, rods, wire, castings. In demand for rich bronze to gold color and for its corrosion resistance. Red brass castings usually carry from 2 to 8% of lead and frequently 3 to 6% of tin.							
2B.	Brazing brass 26% or less zinc; spring brass 28% zinc. Admiralty 29% zinc 1% tin; brass, commercial brass, common brass 30 to 37% zinc; alpha brass, high brass, yellow brass:							
	21 to 37 Zinc 0 to 4 Lead 0 to 2 Tin Rem. Copper	30,000 to 48,000	55,000 to 100,000	15 to 45	1823 to 1634	995 to 890	28 to 20	0.31 to 0.22
	The usual brass of commerce. Sheets, tubes, wire, rods, simple extruded shapes and yellow brass castings. The extruded shapes, rods and castings usually carry lead, sheets and wire usually do not.							
2C.	Muntz metal, Tobin bronze, Naval brass, manganese bronze, beta brass, extruded brass and bronze:							
	37 to 43 Zinc 0 to 1½ Tin 0 to 2 Mn 0 to 1½ Iron 0 to 13 Nickel 0 to 2 Lead Rem. Copper	45,000 to 60,000	50,000 to 90,000	25 to 50	1742 to 1598	950 to 870	26 to 6	0.28 to 0.08
	The yellow bronze, high zinc group (with 7½ to 13% nickel displacing the same amount of copper, the alloy becomes white and is called extruded nickel silver). Good hot forging and extruding qualities. High strength and good corrosion resistance. Sheets, tubes, rods, shafting, gas-welding rods, forgings, extruded shapes and castings. The three last-named products usually carry lead though not necessarily so.							
2D.	Nickel silver:							
	5 to 30 Nickel 5 to 28 Zinc Mn present Rem. Copper	30,000 to 75,000	50,000 to 160,000	30 to 40	1760 to 2228	960 to 1220	12.0 to 3.5	0.14 to 0.05
	Warm white color, good corrosion resistance. Sheet, tubes, rod, wire. Castings may have lead up to 11% and tin up to 5%. Free machining nickel silver rod and sheet may have lead up to 2%.							

Table 1—(*Continued*)

Group No.	Composition,* %	Average Tensile Strength, Psi. Soft	Hard Δ	Elongation in 2 In., % Soft	Melting Point °F.	°C.	Conductivity Elec. % I.A.C.S. 20°C.	Thermal π
3.	Bronze, phosphor bronze, gun metal, bell metal, bearing bronze. The bronze of the ancients improved by suitable deoxidizers:							
	0 to 15 Lead 0 to 4 Zinc 1 to 30 Tin 0.02 to 0.45 Phosphorus Cadmium, see below Rem. Copper	30,000 to 60,000	60,000 to 145,000	15 to 70	1967 to 1418	1075 to 770	45 to 8	0.55 to 0.09
	Characteristic, artistic bronze color. Good strength, wear and corrosion resistance. Good resilience for flat and helical springs. Good tone for bells with 16 to 25% tin. Sheets, rods, wire and welding rods. Wrought up to 10.5% tin, with higher proportions of tin in cast form only. The lead usually appears only in bronze bushings, bearings and castings. Silicon may be used as a deoxidizer in place of phosphorus in non-leaded wrought bronzes. Copper cadmium alloys in wire and rods for electrical purposes carry cadmium up to 1¼%, remainder copper. Additions of tin up to 1% may be made to copper cadmium alloys. With cadmium only in copper, electrical conductivity may be 85% I.A.C.S.							
4.	Copper-silicon alloys, Everdur, Olympic metal, Herculoy, Tombasil, Duronze, PMG metal:							
	0.25 to 5.0 Silicon 0 to 1½ Mn 0 to 5 Zinc 0 to 2 Tin 0 to 2.5 Iron Rem. Copper	40,000 to 60,000	65,000 to 145,000	75 to 20	1931 to 1832	1055 to 1000	12 to 4.5	0.13 to 0.05
	High strength, ductile, forgeable and weldable alloy. Large and small tank sheets, rods, forgings, tubes, wire, bolts, screws, welding rod, castings.							
5.	Cupro-nickel, 30% nickel:							
	2 to 30 Nickel Mn present Rem. Copper	35,000 to 55,000	45,000 to 90,000	30 to 50	2012 to 2237	1100 to 1225	35 to 4.5	0.40 to 0.06
	White (20% of nickel required to completely obliterate the copper red) corrosion-resisting metal. Good resistance to corroding agents such as salt water, etc. See also Chapter 24 on Monel and Nickel.							
6.	Aluminum bronze:							
	1 to 14.5 Aluminum 0 to 4.5 Iron 0 to 5 Nickel 0 to 1 Manganese 0 to 2 Tin Rem. Copper	40,000 to 85,000	50,000 to 125,000	70 to 4	1967 to 1886	1030 to 1075	35 to 7 ΔΔ	0.37 to 0.10 ΔΔ
	Yellow (with 5% or more of aluminum) forgeable, extrudable, corrosion-resisting, non-scaling alloy. Sheets, rods, shafting, wire (low aluminum only), tubes (aluminum not over 5%), forgings, castings, simple extruded shapes.							
7.	Beryllium copper:							
	1.0 to 2½ Be 0 to 1.0 Nickel Rem. Copper	50,000 to 70,000	70,000 to 190,000	45 to 55	1886 to 1742	1030 to 950	45 to 17	0.50 to 0.22
	The highest strength of any copper alloy. Heat treatable and forgeable. Excellent resilience for flat and wire springs and good wear resistance. Sheets, tubes, rods, wire, forgings, castings. The conductivities will vary with the heat treatment as well as the composition.							
8.	*Miscellaneous copper alloys:* In addition to the above groups of copper alloys, there are numerous other possibilities in copper alloy castings, wrought copper alloys and sintered powders. Among these are the heat-treatable *copper-chromium* alloys having an important application as resistance welding electrodes as are the *copper-tungsten* alloys and the less well-known *copper-cobalt-beryllium* alloys. There are many other copper alloys used for highly specialized products which cannot be included in this discussion.							

* In compositions where the low limit of a given element is zero, the element may not appear at all; not to be used for specification purpose. Δ = Hard from cold drawing, cold rolling, etc; normal reduction. π = Cal/cm²/cm/Sec/Deg. C. ΔΔ = Estimated value. Rem. = Remainder. Mn = manganese.

both included in Group 1 but with an A and B designation to indicate certain other features of interest in welding in which they are markedly different. A similar situation exists among the zinc alloys of Group 2 which are subdivided into four subgroups designated A to D, inclusive.

The second column of Table 1 shows the range of the different elements commonly met with in commercial alloys. In Group 2A, for example, we may have (*a*) a straight low brass with no tin or lead, (*b*) a zinc bronze with zinc in any proportion from 5 to 20% plus tin from 1 to 6%, (*c*) a leaded wrought zinc bronze with low lead or (*d*) a red brass casting with lead up to 8%. Thus, in each of the eleven groups, there is a great variety of commercial metals.

The columns on tensile strengths and elongations show the values commonly obtained though they do not show the complete range. Thus a great deal of cold-drawn wire in alloys 2A, 2B, 3, 4 and 7 will exceed the strengths given in column 4 of Table 1. The values for tensile strength quoted in column 3 for the soft base metal apply in some cases to castings. The table does not cover the copper alloys field in detail. The copper alloy manufacturer will have to be consulted for special information on many questions.

In general, the melting point (flow point) and conductivities of the alloy highest in copper in a given group are given first. The electrical conductivity gives a measure of the resistance weldability while the thermal conductivity gives a convenient measure of the heat intensity required in a welding operation. The ductility, as measured by the elongation, is reduced as the cold work hardness increases. The per cent elongation also varies with the shape of the specimen.

COPPER ALLOYS AS WELD METALS

As in Table 1, the different alloys used for welding rods are so numerous as to require condensing into a few general groups. These materials, listed in Table 2, are usually obtainable in welding rod sizes from $^1/_{16}$ in. diameter to $^1/_2$ in. diameter, in the form of granulated spelter solder or in sheet form or cast rods for special cases. Flux-coated electrodes are available in a number of alloys. It will be noted that the group number is followed by the letter "W" signifying welding rod.

In Table 2 the annealed strength of the welding rod is given rather than the strength of the weld metal as there are so very many variables in the welding process affecting the latter that any stated value would be meaningless. The weld metal should approach the annealed welding rod in point of strength.

The more common applications of each group of welding rods are given in the remarks following the tabulation of properties.

WELDING PROCEDURES, COPPER ALLOYS

Owing to the wide diversity of properties in the copper alloy base metals, the optimum welding procedure for any given alloy or combination of alloys is not readily apparent. Hence Table 3 is designed to show at a quick glance just what welding processes are recommended and what others are not. In general, throughout Table 3 *preferences for a given base metal group are indicated for the welding rod and welding process by arranging same in order of preference from top to bottom and from left to right.*

Table 2—Copper Alloys as Welding Rods or Weld Metals

Group No.	Composition, %	Tensile Strength of Soft Red, Psi.	Melting Point °F.	Melting Point °C.
1W.	Electrolytic copper, ordinary copper, tough pitch copper, oxygen-bearing copper:			
	0.03 to 0.07 Oxygen Rem. Copper	32,000	1981	1083
	Ordinary copper wire and sheet, copper powder, electro-deposit. Not recommended for welding rods. Used for copper-hydrogen brazing, electric furnace brazing. (See Chapter 14D.)			
2W.	Deoxidized copper, phosphorus deoxidized copper, silicon deoxidized copper, welding copper:			
	0 to 0.05 Phosphorus 0 to 0.05 Silicon 0 to 1 Silver 0 to 1 Tin Rem. Copper	35,000	1981	1083
	The usual copper welding rod for oxyacetylene welding of copper. Not recommended as bare rods for arc welding—the low deoxidizer content is prone to be lost and the welding metal oxidized in arc welding. Excellent results are obtained with the flux-coated metal arc electrodes.			
3W.	Brazing spelter, golden spelter solder, white spelter solder, black button solder, hard solder—usually in granulated form:			
	42 to 61 Zinc 0 to 11 Nickel 0 to 8 Tin Rem. Copper	....	1742 to 1440	950 to 782
	Brazing of copper alloys, nickel alloys and ferrous metals. See also Chapter 14A. Several silver solders having 40% or more of copper are listed in Chapter 14B.			
4W.	Phosphorus-copper alloy:			
	4 to 8 Phosphorus Rem. Copper	....	1778 to 1319	970 to 715
	Rods and sheets, always hard. Recommended for use on copper base metal only—self-fluxing. Usually applied with gas, occasionally with carbon arc.			
5W.	Tobin bronze, naval brass, manganese bronze, high strength yellow bronze white bronze with 10% nickel:			
	38 to 43 Zinc 0 to 1½ Tin 0 to 1½ Iron 0 to 0.5 Manganese 0 to 0.15 Silicon 0 to 10 Nickel Rem. Copper	45,000 to 60,000	1742 to 1598	950 to 870
	Joining of copper, nickel and ferrous alloys in oxyacetylene welds and brazes of good strength applied at a relatively low temperature. Wear-resisting surfaces, etc. Not recommended for arc welding. See also Chapter 14A.			
6W.	Phosphor bronze for gas welding. Grade E, 1–1.2% tin; Grade C, 8% tin:			
	1½ to 8 Tin 0.03 to 0.05 Phosphorus Rem. Copper	36,000 to 55,000	1958 to 1867	1070 to 1025
	Used for oxyacetylene welding of copper, brass and ferrous alloys. Higher tin alloys used for laying down wear-resisting surfaces. Not recommended for arc welding as bare rods.			

Table 2—(*Continued*)

Group No.	Composition, %	Tensile Strength of Soft Red, Psi.	Melting Point °F.	Melting Point °C.
7W.	Phosphor bronze for arc welding. Grade A, 4% tin; Grade C, 8% tin; Grade D, 10½% tin:			
	1.5 to 10.5 Tin	38,000	1958	1070
	0.05 to 0.45 Phosphorus	to	to	to
	Rem. Copper	60,000	1832	1000
	Used for arc welding copper, brass and ferrous alloys. Wear-resisting surfaces. Not recommended for oxyacetylene welding. Metal arc electrodes are flux-coated and should have low phosphorus.			
8W.	Coppper-silicon alloy, Everdur, Olympic metal, Herculoy, Duronze, PMG metal:			
	1 to 4 Silicon	40,000	1930	1055
	0 to 1.25 Manganese	to	to	to
	0 to 2 Zinc	60,000	1866	1019
	0 to 2 Tin			
	0 to 2½ Iron			
	Rem. Copper			
	High strength welding rod for fusion welding of copper and allied copper alloy base metals and brazing of thin steel. Any method of welding. Metal arc electrodes are flux coated, carbon-arc and oxyacetylene welding rods are used bare or with flux painted on same.			
9W.	70:30 Cupro-nickel:			
	30 Nickel	55,000	2237	1225
	0.1 to 0.5 Manganese			
	Rem. Copper			
	Gas or arc welding rod for cupro-nickel sheet. Metal arc electrodes are heavily flux coated. The gas welding rod is usually deoxidized with silicon.			
10W.	Aluminum bronze:			
	5 to 14.5 Aluminum	52,000	1940	1060
	0 to 4.5 Iron	to	to	to
	Rem. Copper	90,000	1904	1040
	Carbon arc, gas welding rods and coated metal electrodes for aluminum bronze sheet and castings and surfacing of ferrous and non-ferrous metals.			
11W.	Beryllium copper:			
	1 to 2.5 Beryllium	70,000	1886	1030
	0 to 1 Nickel		to	to
	Rem. Copper		1742	950
	Carbon arc-welding rod for beryllium copper sheet and surfacing of copper and ferrous metals.			
SW.	Silver solder:			
	5 to 80 Silver	...	1150	621
	4 to 25 Zinc		to	to
	0 to 5 Phosphorus		1550	843
	0 to 18 Cadmium			
	Rem. Copper			
	Given here for the sake of completeness only. See Chapter 14B for details.			

There are several welding processes in addition to those listed in Table 3 which have more or less important applications in copper alloy welding.

Table 3—Appropriate Welding Methods and Filler Metals for Various Base Metals

Base Metal Group	Welding Process*	Welding Rod (see Table 2)	Remarks on Base Metal
1A, Ordinary Copper	OA MA CA	2W, SW, 3W, 5W, 6W 2W, 7W, 8W all flux coated 7W, 8W, 4W, 11W	High thermal conductivity and oxide embrittlement, chief obstacles to welding
1B, Deoxidized Copper	OA MA CA	2W, 6W, SW, 5W, 3W, 4W 2W, 7W, 8W all flux coated 8W, 7W	High thermal conductivity only obstacle to welding
2A, Gilding, Red Brass, etc.	OA CA R F	5W, 6W, SW, 3W, 4W 7W, 8W Base Metal. See Note R 3W	High thermal conductivity obstacle to resistance welding. Zinc vaporization an obstacle to arc welding
2B, Common Brass, etc.	OA R CA	5W, SW Base Metal. See Note R 7W, 8W	Zinc vaporization chief difficulty in welding. Arc welding not recommended
2C, Muntz, Manganese Bronze, Naval Brass	OA CA	5W, SW 7W, 8W	Zinc vaporization makes arc welding difficult
2D, Nickel Silver, etc.	OA R CA	5W, SW, 3W Base Metal 7W	Zinc vaporization makes arc welding difficult
3, Bronze, Phosphor Bronze	CA R MA OA	7W Base Metal 7W 6W, 5W, SW, 3W	Metal all hot short and subject to liquation. Hence quick welding desired
4, Copper-Silicon	CA R OA MA	8W Base Metal 8W, SW, 5W 8W	Hot short in narrow temperature range close to melting point. Fast welding desired
5, Cupro-Nickel	MA OA R	9W 9W, SW, 5W Base Metal	Nickel oxide and gas absorption chief obstacles to welding
6, Aluminum Bronze	MA CA R OA	10W 10W Base Metal 10W, 5W, SW	Only coated metal arc electrodes are suitabe for metal arc welding. Solid, continuous allu minum oxide film makes gas welding difficult
7, Beryllium Copper	CA R OA	11W Base Metal SW	Solid, continuous films of beryllium oxide make gas welding, at this time, impossible
Steel, Cast Steel, Galvanized Iron and Steel	HF F OA CA MA	1W 3W 5W, 2W, 3W, SW 8W, 7W, 10W, 11W 7W, 8W	Given for sake of completeness. See Chapter 14A and Chapter 14D. Flux required with 3W
Cast Iron, Grey, White Malleable	OA CA	5W 7W, 8W, 10W	Given for sake of completeness. See Chapters 14A and 14D

* Abbreviations for various welding processes used in above table: OA = Oxyacetylene. CA = Carbon Arc. MA = Metal arc. F = Furnace heating. HF = Furnace heating in hydrogen atmosphere. R = Resistance spot and seam welding. Other welding and brazing processes are discussed in a later paragraph.

Note R: Special alloys for resistance welding are made with additions of silicon, manganese or nickel.

Other Welding Processes

(*1*) *Acetylene-Atmospheric Air.*—A clean, moderately high-temperature flame convenient for low-temperature silver brazing and soft soldering copper tubing for interior plumbing and similar purposes. Other gases giving medium temperature flames can be used.

(*2*) *Atomic Hydrogen Arc Flame.*—This flame can be used but has not been exploited to any great extent in copper alloy work.[17] (See Chapter 6.)

(*3*) *Carbon Arc Torch.*—This method of heating gives a lazy, high-temperature, mildly oxidizing flame that is productive of sound weld metal in the leaded brass and bronze alloys and leaded nickel silver.[18, 19] The process is not widely used.

(*4*) *Carbon Resistor Brazing.*—Copper or copper alloy sheets, wires, special fittings, etc., securely held by carbon jaws which are heated white hot by a step-down transformer. Brazing alloys 3W, 4W and SW are applied in powder, rod or sheet form to the work with a flux and melted partly by the heat from the carbon resistors and partly from the high current going through the work itself.

This makes a very convenient and economical method of brazing. There are numerous applications in the manufacture of light sheet-metal parts.[4, 20]

(*5*) *Resistance Butt Welding.*—There are numerous applications where copper and copper alloy wires and rods are resistance butt welded. A special technique is used in which the ends of the work are given the proper heat by straight resistance or by arcing (flashing) to cause fusion, followed by a quick, light pressure push-up. The technique for each application must be worked out separately.[22] In general *the current values are higher, the current-on period shorter, the final push-up faster and the pressure lighter* than is the case when steel is welded. Because the values of time, speed and pressure are so critical, it is quite difficult to get consistently good results manually on copper alloys.

(*6*) *Copper Brazing.*—This process is more frequently used in the manufacture of light machine parts from sheet steel than in the fabrication of copper alloys. Electrolytic copper in wire or powdered form is commonly used as the brazing material, the work being run through a furnace having an atmosphere rich in hydrogen. (See Chapter 14D.)

WELDING PROCEDURES, GENERAL

The following notes form the amplification of Table 3 necessary to make a complete welding procedure for each of the base metals given in Table 1. A practical operator should have no difficulty in applying the given procedure to the welding of any copper alloy provided he can identify it with one of the groups in Table 1 and secure the correct welding rod as indicated in Table 2.

The welding rods listed in Table 2 are all commercially available. A few of them, namely, 2W, 6W or 7W, 8W, 9W and 10W are obtainable with a flux coating designed for metal arc welding.

Preparation of the Base Metal

The base metal should be clean and free of scale and dirt. Graphite, soot and carbon from oil, grease or any carbonaceous matter on the base metal surface will interfere with the proper alloying action of the molten copper alloy weld metal. Such materials should be removed from the welding zone. In the case of oil-soaked base metal, such as bronze bearings, the oil should be evaporated or burned out by a suitable furnace anneal of the base metal.

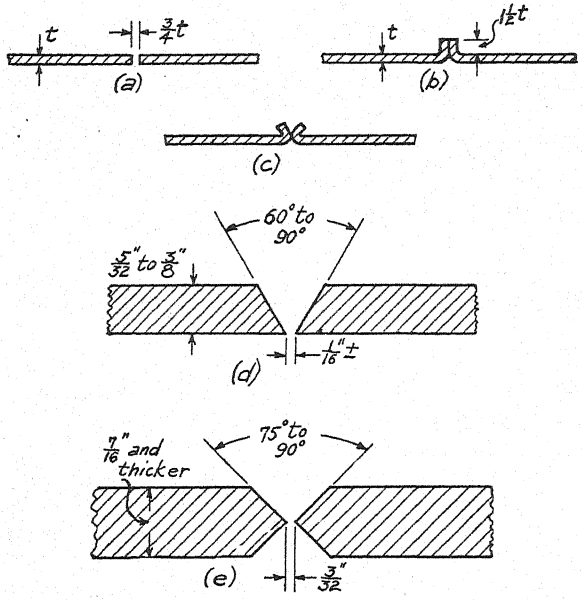


Fig. 1—Preparation of Edges

In the case of a non-pressure butt weld, the edges should be prepared as illustrated in Fig. 1. Figure 1 (*a*), the simplest type of square-edged butt joint, is usable in general for thicknesses from $^1/_{32}$ to $^1/_8$ in. With some of the alloys as, for instance, the Group 4 base metals, Table 1, it is practical to make a square edge butt joint in sheet as thin as 0.025 in. and occasionally as thick as $^3/_{16}$ in. In welding such metals, a round welding rod is sometimes laid on the joint and melted down by the carbon arc simultaneously with the fusion of the base metal.

Figure 1 (*c*) shows one type of bronze weld on thin sheet. The bent-back edges hold the seam rigid during the welding operation and provide a channel for the bronze. The heels of the bends are brought hard together by the shrinking of the bronze weld metal.

Figure 1 (*b*) is used occasionally in base metals which have good fusion welding characteristics. The upturned edges restrain warpage ahead of the welding heat and provide adequate weld metal. The edges are invariably tacked together at frequent intervals or clamped together with small

toolmaker's clamps for welding. Occasionally, the weld metal is obtained from a *single* up-turned edge.

Figure 1 (*d*) and (*e*) are applicable to the heavier sheets to be either gas welded or arc welded. Occasionally, a double vee is used with one side deeper than the other. A U-groove is occasionally preferred in heavy plate.

Figure 2 (*a*) shows the lap seam commonly used in resistance welding and torch or resistance brazing. It should never be used for a gas or arc fusion

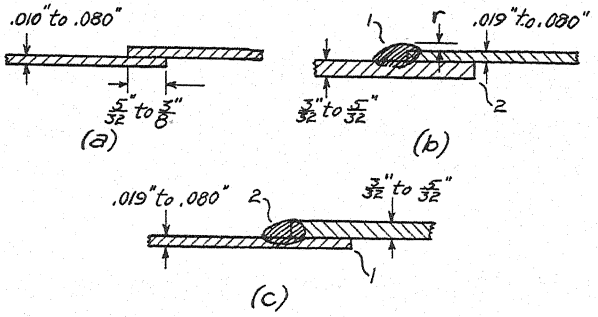


Fig. 2—Lap Welds or Brazes. (*c*) Not Recommended for Fusion Welds, Use (*b*) Instead

weld. Figure 2 (*b*) is a lap seam with one sheet thicker than the other. It may be used for a resistance weld or a braze. An arc or gas weld may also be used in which case the weld should always be made *against* the heavier sheet at edge 1 and never at edge 2 as in Fig. 2 (*c*).

Figure 3 (*a*) to (*h*), inclusive, shows various types of girth seams holding heads or headers to the cylindrical shells. Figure 3 (*a*) is the typical connection for a range boiler. The head being thicker than the shell, the weld is made against it as in Fig. 2 (*b*). Figure 3 (*b*) is a connection design for resistance seam welding the head to the shell.

Figure 3 (*c*), (*d*) and (*e*) are connections used for welding a minus head to the shell. (*c*) Would be preferred normally where the head is thicker than the shell. In (*d*) the weld is easy to make but is in an exposed position. In the case of (*e*) the shell may be of steel while the head is a copper alloy. Design 3 (*f*) is similar to (*e*) but the weld metal is given more surface of contact to both shell and head while the bend in the head flange allows more freedom for the weld metal to contract.

Figure 3 (*g*) and (*h*) are connections holding a *thick*, flat copper alloy header for rolled-in tubes to a copper alloy or steel shell. In (*g*) the header is welded into a flange ring which is butt welded to the shell while in (*h*) the header itself acts as a flange. The inner fillet weld is regarded as important from the standpoint of mechanical strength and also to prevent any corrosive reagent from getting to the root of the outside fillet weld. Where the diameter of the shell is too small to admit of the inside fillet welds being made from the inside, the head may be first welded to a cylindrical ring which ring can be butt welded to the shell afterward.

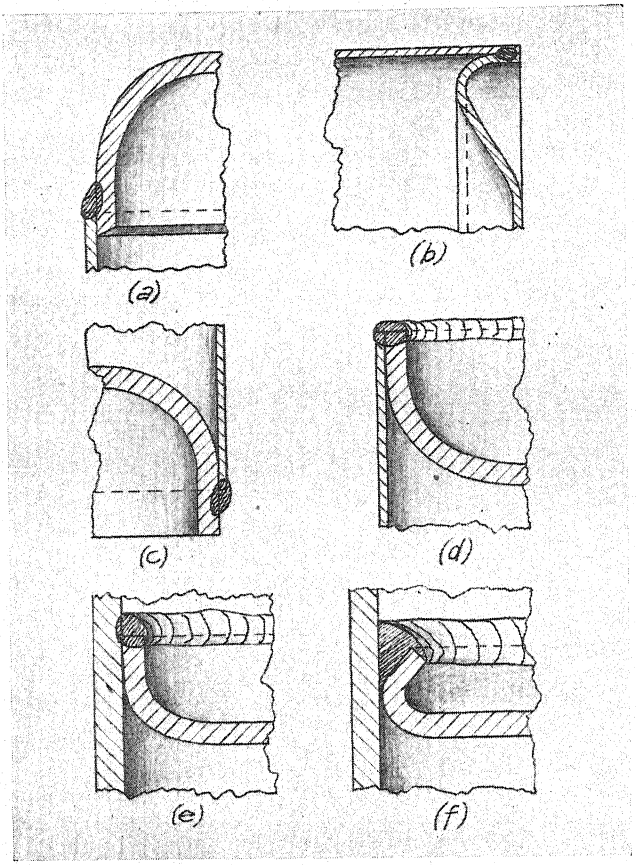


Fig. 3—Welds Connecting Copper Alloy Heads or Headers (Tube Sheets) to Copper Alloy or Steel Shells

Set-up for Welding

As in welding other materials, welds in copper alloys may be run (*a*) as free welds or (*b*) as rigid welds. In general, the root opening will be about 2% of the distance from the end of the seam at which welding is to begin, the exact amount depending upon the speed of welding, the thickness of the plates, the thermal conductivity of the base metal and the coefficient of contraction of the weld metal. When free welds are to be run, the holding jigs should be designed so as to provide only moderate frictional restraint in the plane of the plate. In making rigid welds, the plates are jigged or tack-welded securely together.

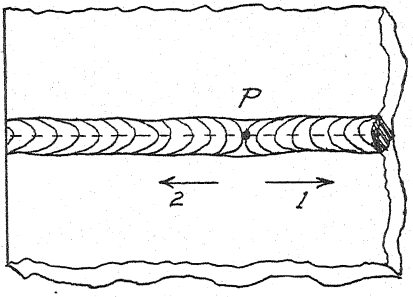


Fig. 4—Starting Point of Second or Later Weld

In making free welds the weld may be started at one end and run through to the other end in one continuous pass. In making the first pass of a rigid weld or the second or later pass of any weld, *the start should not* be made at an end of the seam. It should be started at some point *P*, Fig. 4, remote from the edge, welded to nearest edge in the direction of arrow 1; then, returning to starting point *P*, welded in direction of arrow 2, finishing at the other end. The same procedure should be used if a weld is to be annealed by the slow passage of a torch along the seam.

Backing-up for Welding

In some cases, the weld metal will have sufficient surface tension to allow the weld to be made with no backing up of the weld. More often, it will be necessary to have some bar or strip to retain the weld metal until it solidifies. This is particularly true of arc welding.

In oxyacetylene welding, carbon, asbestos or thin sheet metal will be found desirable. The carbon or asbestos should be channeled under the weld in order to allow complete fusion at its root. The sheet metal backer can be bent to the same end.

In arc welding, copper will be found to be the most satisfactory material for backing up the weld. The copper backer can be machined as shown in profile in Fig. 5. It may be a narrow insert in a steel jig or it may be sufficiently wide as to have the plates clamped directly to it. As shown in Fig. 5, it is relieved by the wide grooves *C* in order to absorb as little as possible of the welding heat.

Flux

In a great deal of copper alloy welding, a flux is desirable and generally necessary. Several common fluxes are listed below with notes on appropriate uses.

(*a*) *Brazing Flux.*—The usual commercial flux for silver brazing, brazing, bronze welding, etc., is a mixture of anhydrous sodium tetraborate, $Na_2B_4O_7$ (calcined borax, fused borax), and boric acid, H_3BO_3. It may be used dry or suspended in water-free alcohol and painted on the work. If mixed in a small quantity and used immediately, it may be mixed with hot water. This makes an excellent flux for alloys carrying copper, zinc, tin, manganese, cadmium, lead and iron.

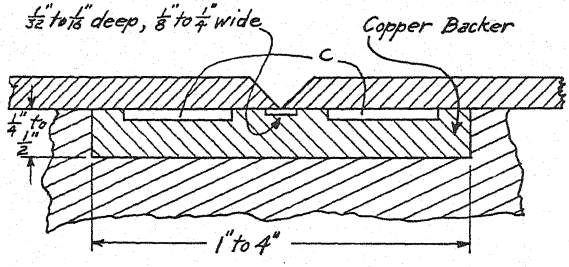


Fig. 5—Copper Backing Set Into Jig

It is moderately successful when silicon is present. It will not dissolve nickel, aluminum, chromium or beryllium oxides and it is not entirely successful in preventing formation of their oxides.

Sometimes, instead of the anhydrous borax, common borax in water is used but it is not satisfactory on account of its crawling away from the heat and thereby exposing the metal. Usually when common borax is employed, the application of the flux to the cold metal has to be supplemented by a second application after the metal is nearly to the brazing temperature.

Many times the flux is mixed with the powdered spelter solders and applied to the work in paste form. This procedure works best in furnace brazing.

Frequently sodium chloride (common salt) is added to the borax base fluxes for the welding of *copper*. It acts as a covering and cleansing agent.

Sodium fluoride or one of the alkaline bifluorides is sometimes added to fused borax when brazing or gas or arc welding the silicon bronzes, Group 4, and the aluminum bronzes, Group 6. The fluoride lowers the melting point of the flux and helps in the dissolving of the metal oxides. A fluoride is sometimes used as a constituent of the flux coating of electrodes containing nickel or aluminum. The vapors, if present in sufficient concentration, from the fluoride fluxes used in gas and arc welding may irritate the mucous membrane or the skin. Hence, good ventilation should be provided when a fluoride-containing flux is used.

No flux for satisfactorily dissolving the oxides of aluminum, nickel, beryllium or chromium as these elements occur in the copper alloys, is

known. However, by the use of boric anhydride, B_2O_3, which is not easily reduced by these active elements and one or more of the alkaline fluorides, a flux is obtained which reduces to a minimum interference from the metal oxides in oxyacetylene or metal arc welding.[37]

Color Match, Corrosion Resistance

In specifying the filler metal to be used with each of the base metals, the facility with which the weld may be made and the strength and ductility of the welded joint have been the principal guiding factors. However, in many cases, the *color match* of the weld metal to the base metal is an important item and in many other cases, the *corrosion resistance* or catalytic effect of the weld metal on the chemicals in process must be identical with that of the base metal. In such cases the welding operator must defer to the ultimate user. Sometimes, where an exact color match is required, as is often the case in architectural and artistic work, it will be necessary to use strips of the base metal for filler metal. Where corrosion resistance is the controlling factor, a welding rod can usually be obtained sufficiently close in composition to the base metal to yield comparable results.

DETAILS OF WELDING PROCEDURES

In the following discussion, the effects of various added elements on the welding properties are evaluated, details of the appropriate welding methods are given and hints as to the results to be expected from variations in the welding procedure are stated. The metals are taken up group by group in the same order as they appear in Table 1.

GROUP 1A COPPER

OXYGEN-BEARING TOUGH PITCH COPPER, ORDINARY COPPER SHEETS, ELECTROLYTIC COPPER, TOUGH PITCH LAKE COPPER

This copper in sheet, rod and wire form usually carries a small amount of *oxygen*, 0.03 to 0.07% in the form of specks of cuprous oxide scattered more or less uniformly throughout the metal. This small amount of cuprous oxide has the beneficial effect of reducing the grain size of the copper and has no harmful effect on the strength, ductility, cold working or electrical properties of the copper.[4]

The cuprous oxide does, however, make the copper carrying it susceptible to gas embrittlement when heated in a hydrogen or carbon monoxide atmosphere to 1300°F. The action is accelerated at temperatures of 1500°F. and above.[5, 6, 7]

Effect of Cuprous Oxide.—Such copper can be readily tinned and soft soldered with no weakening effect due to the cuprous oxide. Silver brazing or phos-copper brazing can also be done with no appreciable loss of strength.

However, when heated to higher temperatures as for fusion welds or for bronze welding, the cuprous oxide causes a loss in strength which may result in a welded strength as low as 12,000 psi. in badly gassed welds

There appear to be two types of weakening effects caused by the cuprous oxide.

The first is occasioned by welding heat alone which if applied for a sufficient length of time causes a rejection of the cuprous oxide to the grain boundaries and this in turn reduces the strength and makes the metal both hot short and cold short.[5] This action is noted in carbon arc welds and may occasion a strength reduction to 21,000 psi. in the area at the edge of the fusion zone. In metal arc welds using a covered copper electrode, the action is less pronounced and strengths in the reduced section weld of 26,000 psi. are not difficult to attain.

The second effect occasioned by a reducing action is more serious particularly in the presence of hydrogen at temperatures of 1500°F. (815°C.) to the melting point around 1981°F. (1083°C.). At this temperature the free hydrogen will penetrate a short distance into the hot solid copper. Encountering some cuprous oxide, a reducing reaction takes place in which water vapor and copper are formed. The water vapor, lacking the power to diffuse outwardly, disrupts the heat-weakened copper resulting in a zone a few thousandths inch back of the fusion line which may have a strength as low as 12,000 psi.[6, 7]

This weakened zone can be corrected by hot forging the weld at a dull red heat[5] and this method has been resorted to frequently in European countries to improve the strength and ductility of welded locomotive fire boxes[8] made of approximately $^{7}/_{8}$-in. thick tough pitch copper. The strength of thinner sheets may be improved by cold working and annealing. But such methods are not often resorted to in this country.

It should be pointed out that this type of weakness *does not occur in deoxidized copper base metal.* Deoxidized copper sheet is therefore preferred when it is to be fabricated by fusion welding.

Heat Conductivity of Copper.—The high heat conductivity of the copper sheet, higher than that of any other industrial metal, is responsible for most of the difficulty in fusion welding it.[8] It is by no means an easy matter to transfer heat from a blowpipe flame or metallic or carbon arc, such as would be satisfactory for bringing steel up to 2800°F. (1538°C.), to a copper sheet of the usual thickness ($^{3}/_{16}$ to $^{1}/_{2}$ in.) sufficient to raise it to a fusion welding temperature of approximately 2000°F. (1093°C.).

A larger blowpipe, higher powered arc or a higher degree of preheat is required to weld copper than is needed for the copper silicon alloys, copper nickel alloys or the ferrous metals.

Preheat in the copper base metal is obtained in some cases from a charcoal fire, from a compressed air and gas or oil torch or from an oxyacetylene blowpipe. Occasionally, it is necessary to use the preheating blowpipe continuously while welding with another. Also occasionally two oxyacetylene blowpipes are used simultaneously for welding, one several inches ahead of the other in a flat weld or the two on opposite sides of a vertical butt weld.[4]

Preheat for carbon arc or metal arc welding is usually obtained from the play of an oxyacetylene torch before the arc welding starts. A good black preheat of 400° to 600°F. is desired.

In addition to the use of preheat or high torch capacity, the heat can

often be conserved in the copper plate by covering it with asbestos sheet.[8] Many times this is as necessary for the operator's comfort as for the heat it will conserve. In some cases, a temporary fire-brick furnace is built around the heavy copper base metal and the operator works through a narrow slit in the sheet metal or asbestos top.

Considerable economy in welding heat is also obtained in vertical welds with two operators working from opposite sides. The two flames must keep pace with one another.

Finally the flame can be directed in a manner that will promote the most rapid transfer of heat, i.e., perpendicular to the weld pool. This would mean down-hand welding but in plates 1/4 in. thick or thicker back-hand welding is generally employed while in relatively thin plates fore-hand welding is commonly used.

Oxyacetylene Welding of Copper

The sizes of oxyacetylene blowpipes for welding copper sheets of various thickness in one pass with preheat from a preliminary play of the torch only are as follows:

Table 4—Oxyacetylene Welding of Copper

Thickness, in.	1/16	1/8	3/16	1/4	3/8
Diam. blowpipe nozzle, in.	0.047	0.070	0.102	0.130	0.147
Acetylene, cu. ft./hr.	9	20	40	62	77

In welding 1/2-in. or thicker plate two 77 cu. ft./hr. torches would be used, the first one welding the first pass about 6 in. ahead of the other.

Filler Rods.—In Table 3 we note a choice of six different welding rods or weld metals for the *oxyacetylene* method of welding. These various metals would be chosen on the following basis:

2W.—Deoxidized copper makes a fusion weld at approximately 2000°F. (1094°C.) with the weld metal as nearly identical to the base metal as is consistent with good practice.

These rods are deoxidized with phosphorus or silicon but *the weld metal cannot correct the oxide embrittlement in the base metal.*[41] After-treatment is necessary if full strength is to be obtained in the weld.

6W.—Grades E or C phosphor bronzes make fusion welds similar to 2W in all respects except that the addition of tin in the filler rod makes the added metal somewhat lower in electrical and thermal conductivity and higher in strength. It will be noted that the phosphorus is kept low in these filler rods. This is necessary for gas welding in order to have a suitable hot ductility.

SW.—The silver brazing alloys make the most satisfactory connections in the electrolytic copper where a lapped connection with lap of approximately three times the thickness can be used. The brazing temperature for most silver solders is sufficiently low so that no oxide embrittlement is developed.

Brazing Copper Bus Bars.—An application of silver brazing to copper bus bars in electrical power houses and switching stations has largely sup-

planted bolted connections. The silver brazed connection has an unchanging conductivity while bolted connections require occasional attention to prevent an increase in resistance at the joint.[42]

These bus bars are overlapped for a distance equal to three times the thickness of the bus and temporarily clamped together with a thin sheet of a silver brazing alloy between. Then, heated with an oxyacetylene blowpipe, the joint is permanently bonded with high mechanical strength and electrical conductivity. Copper butt straps of a length six times the thickness are often preferred to the overlapping of the line members. Equally strong joints are obtained.

One bus bar manufacturer reports good success in fusion arc-welding bus bars with a 1.5% tin, 0.30% phosphorus, 98.2% copper welding rod.[40]

3W, 4W.—The spelter solders and phosphor copper are used where a less expensive brazing solder is desired than the silver alloys. The spelter solders need a flux while the phosphor copper is self-fluxing on a copper base metal.

4W.—The high zinc bronze welding rods make an excellent connection wherever they can be used. While some embrittlement is caused at the bronze welding temperatures around 1625°F. (885°C.) this may be offset by providing a larger bond area, say, twice the thickness of the plate.[27, 28]

Flux for Copper.—A good brazing flux is required for gas welding copper. It is usually mixed to a thin paste in hot water and painted on both welding rods and base metals. It aids in the flowing of the weld metal and helps keep the base metal free of the black, cupric oxide scale.

Arc Welding of Copper

The carbon and the metal arc methods, having little or no hydrogen in the arc atmosphere, cause less embrittlement due to the cuprous oxide in the base metal than is the case with the oxyacetylene flame. Hence, higher strengths can be obtained with the arc than with the gas welding method.[11, 12, 13]

However, in order to avoid loss of ductility due to rejection of the cuprous oxide to the grain boundaries, which is a function of time as well as temperature, the weld should be run fast—10 in. per minute if possible.[12] This means careful preparation and setting up for the weld. A copper backing of the type of Fig. 5 is used wherever possible.

The *7W* phosphor bronze recommended for use with the carbon arc would be a bare rod carrying approximately 0.25% of phosphorus, with 4% tin for the Grade A or 10% tin for the Grade D bronze. The latter has been used more for the *long carbon arc* welding than the former though for some equipment in which similarity of corrosion resistance in weld and base metal is of paramount importance, the Grade A filler rod has been preferred. The Grade D with the higher proportion of tin melts at a lower temperature, flows somewhat more freely at the usual melting temperature, and has a higher strength in the weld metal than the Grade A rod with the 4% tin. These welding rods work best with the long arc, $^5/_8$ to $1^1/_2$ in., corresponding to a voltage drop of 35 to 60 v.

The $^1/_4$-in. diameter rod for the $^3/_{16}$-in. and $^1/_4$-in. plate is satisfactory for completing a 90° single-vee weld in one pass when melted at approximately

Table 5—Data for Long Carbon Arc Welding of Copper, 1A[39]

Thickness of Base Metal, In.	Carbon (Graphite) Electrode, Diam., In.*	7W Phos. Bronze Welding Rod, Diam., In.	Approximate arc Voltage	Approximate Current Amp.
1/16	1/4	1/8	30	125–225
1/8	5/16	3/16	40	175–350
3/16	5/16	1/4	45	200–400
1/4	3/8	1/4	50	250–500
3/8	3/8	3/8	60	350–600
1/2	7/16	3/8	60	600–800

* These diameters are smaller than those recommended by the carbon manufacturer for the amperages given. The carbon with these high current densities does not burn blunt as rapidly as would be the case with a large diameter nor does it throw down as much carbon black on the work.

1 in. of rod per inch of weld while the 3/8-in. diameter rod for the 3/8-in. and 1/2-in. plate will have to be fed in at the rate of more than 1 in. of rod per inch of weld for one pass welds. One-half inch diameter rod could be used on the 1/2-in. plate but there is danger, even in the flat welding position, that the weld metal will flow ahead on the cold plate.

The wide variations in current values are given because of variations in set-up, such as heat capacity of backing, etc. Sufficient heat to run the weld at 5 in. or more per minute should be used even in the most difficult situations. The base metal is commonly not fused but is heated nearly to fusion by the play of the arc flame and the superheated weld metal. The arc is directed entirely on the weld metal even at the starting point.

Owing to the high heat intensities resulting in a very fluid weld metal, only flat welding or welding up a moderate slope is feasible. *Long arc welding is unsuited to position welding.*

Welding rods of the copper-silicon alloys, 8W, may be used on base metal 1A when the service conditions to be encountered by the welded metal do not inhibit the use of a copper-silicon alloy. A high welding speed and current value are necessary as in the case of the phosphor bronze, 7W alloy, rods but a short arc is commonly employed instead of a long arc. A coating of flux made up of 90% powdered fused borax and 10% sodium fluoride on base metal is quite helpful.

The copper-phosphorus alloy, 4W, is sometimes used in making electrical connections to transformer leads, etc. A considerable proportion of the phosphorus is evaporated from the weld metal but this is beneficial rather than otherwise in an electrical connection because the electrical conductivity improves with diminishing phosphorus.

The copper-beryllium alloy, 11W, on copper base metal, 1A, is used as hard surfacing alloy only. The principal application is on copper grips for resistance welding machines and wear-resisting surfaces.[36] The long carbon arc is necessary. Carbon dams are required to retain the intensely heated, very fluid weld metal. The base metal should not be fused though very highly heated by the superheated weld metal and a suitable dark preheat.

In *metal arc welding of copper*, the set-up with a copper backing bar is the same as for welding with the carbon arc. A thin coating of a finely pow-

dered brazing flux on the base metal helps to protect it from oxidation and a flux coating on the welding rod improves the soundness, strength and ductility of the weld metal.

The 2W flux-coated electrode makes a joint with properties quite similar to those of the base metal.

The *approximate current values* required for these coated deoxidized copper electrodes in welding various thicknesses of copper sheets are given in Table 6. In order to avoid a cold lap at the start, the sheets should be given a preheat of 500 to 600°F. and the arc held as short as possible with electrode positive.

In using these electrodes, the edges of the copper sheets thicker than $^1/_8$ in. should be beveled 45°. One-eighth inch thick plates are spaced $^1/_{16}$ in. apart. A copper backing is used for all thicknesses. Plates up to $^3/_8$ in. are welded in one pass but frequently a cover bead is found desirable on the bottom. One-half inch or thicker plates may be welded in three or more passes. However, in order to conserve heat, it may be found desirable to complete the several passes in short sections rather than run the entire weld one pass at a time.

Table 6—Current Values for Deoxidized Copper, 2W, Coated Electrodes

Electrode core, Diam., In.	$^1/_8$	$^3/_{16}$	$^1/_4$	$^5/_{16}$	$^3/_8$
Amperes	160	220	290	400	520

Coated phosphor bronze electrodes and silicon copper, 8W, electrodes are commercially available but their use on copper or deoxidized copper has not gained wide acceptance.

Resistance Welding of Copper

Resistance spot and seam welding of copper, 1A, has been tried many times but not with sufficient success to consider it commercially practical. The electrical and thermal conductivities are so high that this method requires an extremely high current and unusually short heat-on periods.[22] The usual copper or copper alloy electrodes are not likely to give a satisfactory service life and tungsten electrodes run so hot that the outside surfaces of the base metal soften too much.

Resistance brazing with heat obtained largely from carbon resistor electrodes[9] is a more practical application and is quite satisfactory for some purposes.

Resistance butt welds on copper wire and rods are made commercially, the full strength of the soft metal being obtained with a correct set-up. Manual operation is difficult and a cam-controlled cycle for a given size of rod or wire is more certain.

DEOXIDIZED COPPER, GROUP 1B

Copper deoxidized with silicon, phosphorus or other active deoxidizer is a decidedly easier metal to weld than the oxygen-bearing copper.[4] It should

be used in equipment fabricated by welding in all cases where it is satisfactory for the ultimate service of such equipment. Phosphorus has been the deoxidizer for copper for welding but silicon deoxidized copper has greater hot ductility than phosphorus deoxidized copper. For some special apparatus, oxygen-free high conductivity copper or high conductivity deoxidized copper may be required. Such copper should be handled much as deoxidized copper but with exceptional care being exercised to keep it free of oxides.

The thermal and electrical conductivities of deoxidized copper are in general lower than similar properties of Group 1A but still high enough to be a real problem for the operator in any method of welding. Table 4 applies as much to deoxidized copper as to the tough pitch copper. The essential difference is that, since it has no oxide inclusions, the deoxidized copper is subject to neither of the weaknesses outlined for the oxygen-bearing copper. It is not subject to oxide embrittlement nor to the hydrogen attack. Hence, it is a much safer metal to weld.

The *oxyacetylene method* is often preferred for welding deoxidized copper and, where a suitably strengthened filler rod is used, the full strength of the soft base metal is not difficult to attain. The *silver* addition helps slightly toward lowering the melting point and in keeping the grain size of the weld small. Very little gain in strength is obtained by the 1% silver addition. The *tin* of the welding rods, 2W and 6W, is more efficacious on this score. In general the preparation of the edges, use of preheat and methods of conserving the welding heat, as described in the foregoing for oxygen-bearing copper, are applicable.

For oxyacetylene welding, the phosphorus of alloys 2W and 6W should be low, 0.02 to 0.05%, while the silicon may be several times this amount without causing any serious lack of ductility in the red hot metal.[4]

Silver brazed joints or spelter brazed joints are quite satisfactory in point of strength and ductility. A $22^1/_2$ to 30° scarfed joint should develop the full strength of the soft copper. Such a joint made with silver solder may be cold worked to any desired degree.

Bronze-welded connections with 5W alloys are strong, ductile and easy to make for apparatus where this combination of a high zinc bronze weld metal and the deoxidized copper base metal is not objectionable. The fabrication and position welding of large diameter copper pipe by bronze welding for handling the solutions in a large paper mill have been found to be practical and economical.[28]

Bronze-welded connections in copper tube and brass pipe plumbing installations in England have proved very satisfactory in service and economical to make.[9]

To *carbon arc welding* of the deoxidized copper sheet, Table 6 applies equally well. Since there is no danger of oxide embrittlement, speed of welding is not so essential. Lower current values may be used and the operator may move more slowly than is desirable for tough pitch copper. However, in working with the 7W phosphor bronze welding rods, one must not hold the arc long enough on a given weld pool to evaporate out all of the phosphorus deoxidizer. To do so would cause serious oxidation of the weld metal.

Another advantage arising from the use of deoxidized copper base metal

is that the lower allowable speed tends to improve conditions for position welding with the carbon arc when an 8W copper-silicon welding rod can be used. Most of the carbon or metal arc work will have to be done downhand and the oxyacetylene method and 2W or 5W filler rods relied upon for vertical or overhead work.

In *metal* arc welding, the commercial availability of the *flux-coated* 2W metal arc electrodes improves the desirability of this method greatly though it is still necessary to use the oxyacetylene blowpipe or other preheat to bring the base metal up to a suitable starting temperature of 500 to 600°F. Besides the 2W covered electrodes 7W and 8W covered electrodes are commercially available but have not gained wide acceptance for the 1B base metal.

Resistance spot and seam welding is nearly as difficult with deoxidized copper sheet 1B as it is with tough pitch copper 1A. When fabrication by this method is desired, it is much more to the point to use a silicon brass, a copper silicon or copper-nickel alloy.

GROUP 2A RED BRASS, ZINC BRONZE, LOW ZINC BRASS

Usually this base metal in sheet form is a straight copper zinc brass. Tin is occasionally added to improve the strength, hardness, wear resistance and resilience of the alloy. *Lead* is occasionally added to the wrought alloy to promote free machining. It is generally present in red brass castings as droplets of pure lead. The casting and machining qualities are improved thereby. A considerable proportion of red brass castings is used for pipe fittings, valve bodies and other hydraulic work calling for good wear and corrosion resistance.

Lead gives trouble in the oxyacetylene fusion or bronze welding of brass castings by sweating to the surface at temperatures not greatly above its melting point, 620°F. (327°C.). It oxidizes at higher temperatures and the unstable oxide interferes with the welding operation. However, by the use of an *oxidizing flame*, which stabilizes the oxide, and plenty of brazing flux, trouble from this constituent is minimized.[27]

Zinc in Brass.—In all copper-zinc alloys, Groups 2A to D, inclusive, the one feature that concerns the welding operator most is the tendency for the zinc to vaporize from the molten metal. Pure zinc melts at 787°F. (419° C.) and boils at 1665°F. (970°C.). Alloyed with copper, its vapor pressure is partially suppressed so that the molten brass has to be superheated before an *appreciable* amount of zinc vapor is evolved. The zinc vapor is easily recognized since, on contact with the air it burns to the familiar white zinc oxide smoke.

As this vapor pressure is a function of temperature, it is probable that no flux coating or gaseous shielding can be devised that will enable one to make a satisfactory metal arc electrode of brass wire or rod. The high temperature of the carbon arc prevents its being a satisfactory method for melting a zinc-bearing filler rod.

There are three methods of keeping down the zinc vapor: (*a*) By keeping the temperature to the minimum necessary for the fusion-welding or bronze-welding operation. In furnace brazing or blowpipe welding or

brazing, this can readily be accomplished. A skilled operator will deposit the brass or zinc-bearing bronze with no appreciable amount of zinc oxide smoke. (*b*) By allowing a layer of oxide to form on the molten metal.[15] This method is frequently resorted to in oxyacetylene welding. The blowpipe *is turned oxidizing* to the point where a crust of oxide forms on initially melting the metal. This slows up further oxidation of the molten metal. This method is applicable to the welding of brass, architectural bronze, cast brass and extruded brass shapes. The atmosphere of the carbon arc torch with its mildly oxidizing and carbon vapor atmosphere serves very well in this regard. (*c*) By the use of a film-forming element in the brass base metal or welding rod. There are many such film-forming elements but only a few are useful. The aluminum in brass forms a tough oxide film which keeps down the zinc vapor but it is decidedly objectionable on account of its refractory and unfluxable nature. The same is true of vanadium, chromium and beryllium. Manganese gives partial coverage but the most effective agent of this character is silicon. The silicon oxide forms with copper and zinc oxides a flux-like liquid glass which stays molten and gives perfect coverage until the metal solidifies.[26, 31]

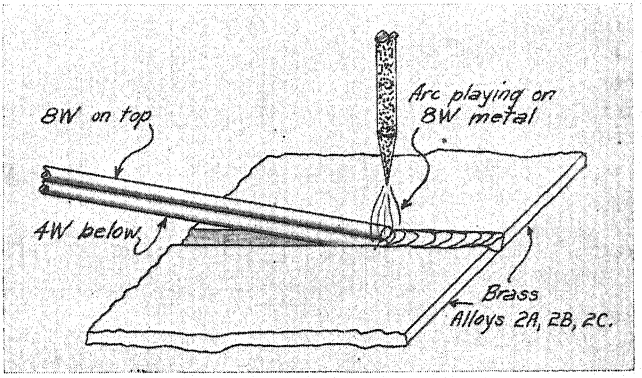


Fig. 6—Welding Brass with Carbon Arc and 8W and 4W Rods

An exact welding procedure for any one of the red brasses of Group 2A will depend upon the purpose for which the work is desired. Usually in *oxyacetylene* welding, the yellow bronze filler rods, 5W, will produce a strong, ductile braze without fusion of the base metal and with a reasonably good color match to the 15% and 20% zinc brass. Where an *exact color match* is required, it may be necessary to use strips of the base metal.

A good *brazing flux* is always required. An *oxidizing flame* helps keep down the zinc vaporization and improves the soundness of the weld though it is likely to be a slower flame than the neutral with the same blowpipe.

For position welding of red brass pipe installations, the 5W yellow bronze filler rod and the oxyacetylene method is preferred.[32] The 6W phosphor bronzes could be used if a color match is required for a gilding metal or commercial bronze.

The 2A red brasses are readily silver brazed or spelter brazed with SW or 3W materials or joined with the 4W phosphorus copper. An oxy-

acetylene blowpipe or furnace heating may be employed. Electric resistor brazing is equally satisfactory for thin sheets.

The *metal arc* is not recommended on account of the severe zinc vaporization from the base metal. The *carbon arc* is a possible method of welding if a zinc-free filler rod such as the 7W phosphor bronze or the 8W copper-silicon alloy is used. In this case the arc is played entirely on the weld metal and not at all on the base metal.

Resistance spot and seam welding are not recommended as methods of joining the straight copper zinc alloys. The thermal and electrical conductivities are still rather high. However, *special silicon-bearing red brasses and common brasses are commercially available and excellent results may be obtained with them.*[22, 23]

GROUP 2B, COMMON BRASS

General.—These more common of the brass alloys have a sufficiently low melting range and heat conductivity to make oxyacetylene welding comparatively easy. If the yellow bronze welding rods, 5W, are used, the bronze weld is in general a *fusion weld* and not a braze.

The SW *silver solders* are the only brazing materials with melting points sufficiently low to make possible satisfactory overlapped or scarfed brazes.

The 2B common brasses are even less amenable to welding by the *carbon or metal arc* than the 2A red brasses. The metal arc is not recommended in any situation.

The *carbon arc* can be made to work after a fashion if a zinc-free filler rod such as a phosphor bronze, 7W, or copper-silicon alloy, 8W, is used and the arc kept on the filler metal rather than the base metal. One writer describes a great variety of work in ship fitting using the carbon arc on brass and bronze.[16]

The electrical and thermal conductivities of the common brasses are much lower than for copper or commercial bronze. They are, however, still much higher than similar properties for steel, copper-silicon and copper-nickel alloys. Hence, while common brass may be *resistance spot and seam welded*, it is decidedly preferable to use a special silicon brass for sheets which are to be resistance spot welded. Such brasses are commercially available.[23, 24, 25]

The *oxyacetylene* method is, without doubt, the optimum welding method for common brass, 2B. While the temperature of this flame is high enough to make rapid vaporization of the zinc a hazard with careless operators, it is quite possible to avoid this condition entirely. Thus, if the temperature of the molten metal is kept to within a few degrees of the melting point by a suitable adjustment of size and direction of the blowpipe flame aided further by suitable manipulation of the melting end of the welding rod, there will be little or no vaporization of zinc.

Also, if the torch flame *is turned oxidizing by throttling of the acetylene*, an adjustment will be reached which will develop a slight oxide film on the weld pool stopping completely further vaporization of the zinc at the usual welding temperatures.[15] This oxidizing torch adjustment, estimated at 30% excess oxygen, also promotes soundness in the weld metal of the brasses and in particular those that have lead in their composition.

Special *fluxes*, which are designed to cover the weld pool with a suitable film, are a material aid in suppressing zinc vaporization and in obtaining sound weld metal.

The 5W yellow bronze welding rods will be found most satisfactory for this work. As pointed out above the joint is practically a straight fusion weld.

MUNTZ METAL GROUP, 2C

General.—These high zinc or beta brasses carrying 36 to 42% zinc include also sheet metal similar in composition to the 5W yellow bronze welding rods, Tobin bronze and manganese bronze. The 2C brasses are usually made up of mixed crystals of the alpha and the beta components while the 2A and 2B brasses have only the alpha constituent. The beta constituent is harder and stronger than the alpha when at room temperature and softer when hot. Hence, these 2C alloys are preferable for hot working as forging, hot rolling and extruding and less desirable than the alpha brasses for cold working.

Lead is kept strictly out of the 5W welding rods on account of its unfavorable drossing and hot short effect on the weld metal. The lead is, however, desirable for promoting machinability in much of the base metal, and it aids in the solid flow of the 2C alloys in the extrusion and the forging dies.

The *tin* improves the strength and flowing characteristics while *tin* and *iron* together in the manganese bronze improve the hardness and wear resistance.

Manganese also improves the wear resistance, though in most manganese bronzes it is present in very small proportions.

Nickel is added only when a white color is needed. It does not, in this alloy, change the welding characteristics greatly. The nickel depresses the thermal and electrical conductivity so that less heat is required for welding.

A good *brazing flux* is a prerequisite for welding.

Oxyacetylene welds in the 2C base material are strictly fusion welds using 5W yellow bronze welding rods. The heat conductivity is still rather high as compared to that of steel, for instance. Hence, a rather large torch flame is found necessary.

The Muntz metal alloys, 2C, can, of course, be silver soldered with the SW group. The brazing spelter solders, 3W, have no advantage over the welding rods of 5W alloy.

Zinc vaporization may be suppressed by using an oxidizing flame as described for alloy 2B above. A strongly oxidizing flame (30% excess oxygen) also promotes soundness in the leaded extruded brasses and bronzes.[27] Hence in making mitered joints for architectural designs, where the joint is to be polished, the oxidizing flame should be used while in welds made from the back, the neutral flame may be found preferable because of its greater economy and speed though it will not produce as sound a weld.

While 5W yellow bronze weld metal is quite a good color match to most of the beta brass, 2C, base metals, there are cases on polished surfaces

where, being free of lead, it offers some contrast in color to the leaded base metal. In such a situation, it is best to use strips of the base metal for welding rod, applying same with an oxidizing flame.

The 2C group metals *are not commonly metal arc welded, resistance welded or brazed.* Where thin rolled sheets are desired, alpha brass is usually found preferable.

It is, however, possible to *carbon arc weld* the 2C alloys if the requirements for color match and strength are not too high. A 7W or 8W welding rod would be used in this case and the arc kept strictly on the filler metal and not on the base metal. One investigation[13] showed only moderate strength in such a weld.

In joining extruded architectural shapes which are rarely more than $^1/_8$ in. thick, the closely fitted corners can sometimes be welded from the back, the joint showing as a thin hair line on the front.

NICKEL SILVER, GROUP 2D

General.—These metals are used for their artistic merit where a white metal is desired and for their good corrosion resistance. As compared to the yellow brasses, the usual 15 to 20% nickel makes the nickel silvers easier to weld in one respect—the thermal and electrical conductivity is much lower—and more difficult in another—the increased gas absorbing capacity is inclined to promote porosity. The nickel oxide would add to the difficulty were it allowed to form. However, by the use of a suitable flux protection, the formation of the nickel oxide can usually be forestalled.

As will be noted from Table 3, the *oxyacetylene method* is given first choice though the excellent resistance-welding properties of the nickel silvers make the latter method the optimum in some lapped connections.

The 5W white high zinc bronze is given a decided preference. Applied by the oxyacetylene blowpipe, it makes a strong bronze weld with a reasonably close color match to the usual nickel-silver sheet. In extruded nickel silver, which also has high zinc, the 5W welding rod makes a straight fusion weld.

Silver Solder, SW, is found useful in making many connections. It is accorded second place as it gives a good color match and is easily applied. The white spelter solder, 3W, is also quite satisfactory for many purposes though its higher melting point makes it more difficult to apply than the silver solders.

The principal points to be observed in the gas-welding procedure are: (1) Starting with clean metal, coat base metal and welding rod with a good brazing flux mixed into a creamy paste with boiling water before the heat is applied. (2) Run the weld as nearly continuously as possible using the neutral flame. An oxidizing flame may, however, be preferable in welding the leaded extruded nickel-silver shapes in order to avoid unsoundness from the action of the lead.

It is possible to make *carbon arc* welds using the 7W phosphor-bronze welding rods or the 8W copper-silicon welding rods. Neither of these welding rods makes a color match with the nickel silvers. *Metal arc* weld-

ing on these alloys is not recommended on account of the severe vaporization of the zinc.

The high electrical resistance and low thermal conductivity make these nickel silvers easy to *resistance spot and seam weld*.[22] The current values are little if any higher than those required for steel of the same thickness. As in the resistance welding of most copper alloys, the pressure should not be too great and should be held within narrow limits. A short heat-on period is desirable. In resistance butt welding, the zinc is prone to vaporize though moderate strength connections may be made.

PHOSPHOR BRONZES, GROUP 3

General.—In this group, the wrought phosphor sheet and wire containing from 1 to 10½% of tin, the cast gun metal containing 9 to 11% of tin and the cast bell metal containing 15 to 26% of tin have as a rule no lead and only a few hundredths per cent of phosphorus. The cast bearing bronzes carry from 4 to 15% tin with lead from a fractional per cent to 25%. The cast statuary bronzes usually carry 1 to 2% of lead and 4 to 8% tin. Some of the above bronzes are deoxidized with zinc rather than phosphorus.

Most of the above alloys do not have sufficient phosphorus to insure thorough deoxidation when the base metal is melted in the direct arc. Hence, tin oxide and, in some cases, lead oxide are likely to be developed in the weld metal. Tin oxide is not readily floated out so that, if allowed to form it is likely to make the weld metal porous and weak. The best way to avoid this difficulty is to keep the arc off the base metal, playing same on a weld metal which has sufficient phosphorus to insure deoxidation.

The metal is for the most part inclined to be hot short and subject to inter-dendrite shrinkage of the lower melting constituents. Thus, a wide-spreading heat and slow cooling is likely to produce hot short cracks and porous places in the weld metal of a straight fusion weld. A narrow heat zone with quick solidification promotes soundness.

The *oxyacetylene* method of welding is placed last in Table 3 for the phosphor bronzes because of the relatively great contraction that takes place while the metal is solidifying from the welding heat. This is prone to cause hot short cracks. However, this does not mean that there is any unsurmountable difficulty in oxyacetylene welding the Group 3 bronzes. Welds using phosphor-bronze welding rods, 6W, are necessarily fusion welds while with the high zinc bronze filler rods, 5W, the base metal need not be fused.

When there is no objection from the standpoint of color match or subsequent usage, the high zinc bronzes, 5W, will be found the easiest metals to apply with little danger of hot short cracks. The low phosphorus in the 6W phosphor bronze rods minimizes difficulties from this source.

With either of the above filler rods a good brazing flux is required. The neutral flame is preferred unless the base metal is high in lead in which case the oxidizing flame may result in less unsoundness.

In welding the higher tin alloys, as, for instance, bell metal of 20 to 25% tin, the remainder copper, a reasonable degree of preheat is *desirable* if the

filler rod is manganese bronze and *necessary* if the 6W phosphor bronze filler rods or a cast bronze of a higher tin content are used.

No difficulty is to be expected in *silver brazing* the Group 3 metals. Or they may be brazed with the usual spelter solders, 3W.

The *carbon arc* using the 7W high phosphorus bronze welding rods is perhaps the *preferred* method of joining the Group 3 base metals. The phosphorus in the filler rod is sufficient to forestall oxidation of the weld metal even if the latter is given a reasonable degree of superheat. Moreover, with this concentrated heat, the contraction strains are reduced to a minimum so that there is little danger of overstressing the weld metal while it is in the hot tender stage.

With the carbon arc, it is generally unnecessary to resort to preheat. Thus in the welding of heavy bronze bells, if the metal is laid in a little at a time and peened immediately, comparatively little locked-up stress will be developed.

The 7W wrought phosphor-bronze welding rods should be used wherever possible though in the case of a 75:25 copper-tin bell, and some of the bearing bronzes, it may be necessary to use a high tin, cast rod. The latter should have sufficient phosphorus in it to keep the weld metal free of oxides. A *flux* is desirable though not necessary. Since the weld metal is very fluid, only flat, or nearly flat, welding is possible.

Several flux-coated phosphor-bronze *metal arc electrodes* have been made available commercially. These make welds in the Group 3 phosphor bronzes of good strength and soundness. It is probable that, with the coated electrodes properly qualified, this method will be preferred to either the gas or the carbon arc method.

The 7W phosphor-bronze bare filler rods used with the carbon arc or the coated electrodes used with the metal arc find a very useful field of service in the making of *wear-resisting surfaces* on rolled and cast steel and cast iron.[38]

With either method of application, it is desirable that the arc play on the phosphor-bronze weld metal rather than on the ferrous base metal. The latter should never be allowed to fuse since fusion would cause droplets of the base metal to float up into the bronze wear-resisting surface and defeat in a measure the object of the latter. However, it is important to get sufficient heat into the base metal to secure a good bond. Usually this will be a temperature that will "wet" the surface. The bond can be tested by driving a cold chisel under the bronze deposit. In coming away, the bronze should bring particles of steel with it.

Since the welding rod size and heat required will depend upon the character of the base metal, no definite figures can be given. The welding rods, 7W, vary from $^1/_8$ to $^1/_2$ in. in diameter and the heat required from 150 amp. to 800 amp. with arc voltages ranging from 25 to 60 v.

In general, only flat or nearly flat welding can be done. And in some cases copper or carbon dams are necessary to hold the very fluid weld metal. Bare rods are used for carbon arc surfacing and bare rods in the larger sizes are used for metal arc surfacing.* 7W rods in the sizes $^1/_8$ to $^1/_4$ in. are obtainable in flux-coated form where a sounder deposit is desired.

*See also Chapter 15B on Bronze Surfacing.

The *resistance spot and seam welding* is applicable only to phosphor bronze in sheet and wire free from lead. It welds at a lower heat and at about the same pressure as brass. Strong, sound spot and seam welds are readily made in the usual thicknesses. Resistance welding is preferable to the carbon arc on cold-rolled phosphor bronze sheet, if a proportion of the cold work hardness is to be retained. The one difficulty sometimes encountered is that there is a tendency for the copper electrodes to weld to the base metal or mar its surface by picking out particles of metal therefrom.

COPPER-SILICON ALLOYS, GROUP 4

General.—When a copper alloy for fusion welding is desired, the Group 4 copper-silicon alloys are usually accorded first choice. Though they commonly carry 96% of copper, the welding of these alloys is facilitated by a low heat conductivity, by a continuous, protective, liquid glass film on the metal, the instant it is melted, and by excellent ductility both hot and cold except for a narrow temperature range close to the melting point. Much detailed work in the welding of this group of alloys has been done which cannot be detailed herein. Hence it would be well in starting the manufacture of such metal products by welding methods to consult the manufacturer of the copper-alloy sheet.

Generally speaking, the oxyacetylene weld metal has large grains with excellent ductility and moderate strength of the order of 52,000 psi. The carbon arc-weld metal has a finer grain and it is slightly stronger and slightly less ductile than that of the gas welds. The metal arc weld, using the bare 8W copper-silicon electrode, is slightly inferior in both tensile strength and ductility to the carbon arc weld. Welds made with *flux-coated electrodes* show considerable improvement in both strength and ductility over metal arc welds made with the bare electrodes.

The *film* on the weld pool is sufficiently fluid in the intense heat of the carbon arc or metal arc as to require little *flux* though a light dusting or thin wash of the 90% fused borax plus 10% sodium fluoride flux in alcohol is desirable. In oxyacetylene welding, the film is more viscous and a liberal application of a brazing flux rich in boric acid is necessary. A small weld pool with fast solidification helps to keep the grain small and to avoid trouble from the contraction strains during the hot short temperature range just below the solidus. The film helps hold the molten metal in place, thus facilitating *position* welding, though flat welding is recommended in normal practice.

Set-up for Welding.—Oxyacetylene welds, on account of the spreading heat and high contraction strains, are best made as free welds. Jigs, therefore, should hold the base metal in position allowing the two edges to draw together from an opening of 2 to $2^1/_2$ per cent as the weld progresses. Welds of two or more passes and welds made on rigidly held sheets are possible—care being taken to start the weld from some inside point as in Fig. 4.

Carbon arc and metal arc welds are usually made with the work held or tack welded rigidly in position. The carbon arc and metal arc welds are usually made against a grooved copper backer as in Fig. 5. Oxyacetylene welds are ordinarily made without a backing.

After-Treatment.—Welds in the copper-silicon alloys made by the carbon or metal arc are improved in both tensile strength and ductility by peening

with an air hammer and annealing. The peening should be done on the cold or dark hot metal for every $^3/_{16}$-in. thickness of deposit. The welding heat from the next bead will serve to anneal and recrystallize the layer which has been peened previously. The outside layer after being peened must be annealed by the slow passage of an oxyacetylene torch along the seam which brings the metal to a dull red heat.[29]

Ordinarily, oxyacetylene welds have sufficient ductility and strength. However, both of these properties as well as the grain size can be improved by hot forging the weld metal at a dull red heat.[30] Seams in relatively thin metal, say, $^1/_{16}$ in. and thinner, can best be improved by cold hammering and annealing.

The flame for *oxyacetylene* welding works best with a slight excess of oxygen. This makes a smaller weld pool than the neutral flame while the excess oxygen does no harm to the metal protected as it is by the impervious film of molten silica glass.

With the 8W copper-silicon welding rod, the weld becomes a straight fusion weld. The base metal must be fused simultaneously with the welding rod in order to secure the maximum strength. The statement is emphasized because an operator, unfamiliar with the metal, is prone to place the filler metal much as bronze is laid on the hot solid base metal in bronze welding. *Such procedure does not* develop the full strength though the weld metal appears to "tin" the hot solid base metal avidly.

Where the weld is run in two or more passes, the first pass is usually run as a free weld with approximately $2^1/_2\%$ opening, the groove being filled about one-third full. Owing to the low thermal conductivities of the Group 4 alloys, it is not commonly advantageous to work with two torches as is recommended in thicker sheets of copper and deoxidized copper, 1A and 1B.

Brazing.—The copper-silicon alloys of Group 4 may be *silver brazed* with the SW alloys by the usual procedure. The metal must be clean to start with and it is important to cover with a low melting flux (brazing flux mixed with the alkaline bi-fluorides) in order to keep the silicon oxide from forming in the heating-up stage.

The base metal must be in the stress-free or nearly stress-free condition at the time the molten solder is laid thereon as otherwise the bronze will crack the copper-silicon alloy by inter-granular penetration.

The 5W yellow welding bronzes can be used on the copper-silicon alloys as readily as on copper or steel and by the same procedure. The precaution must be taken to start with clean metal and cover with brazing flux to protect the metal from oxidation in the heating-up stage. The bronze can be deposited on the solid copper-silicon Group 4 metal as soon as the latter arrives at a good "tinning" temperature.

Bronze welding is not applied commercially to the joining of the Group 4 alloys to any great extent as the fusion weld with 8W settles the questions of color match and relative corrosion resistance of weld metal and base metal.

The *metal arc* has the advantage of highly localized heat which, once correctly determined, is nearly uniform for a given size rod. The long drops forming on the end of the *bare* rod make the *flat* position necessary. For the same reason an arc voltage of 25 to 30 is required. Several coated 8W electrodes designed to overcome these features of the bare rod have re-

cently been offered commercially. As was pointed out above, the 8W *covered metal electrodes*, when properly handled, yield welds of excellent strength and ductility.

Owing to the ease of control of the metal with the *carbon arc*, this method is preferred by many operators.[33, 34] With moderate current values and an arc voltage held below 25, vertical welding can be done though the flat position is generally preferred. Welding in the overhead position requires a high degree of skill. The metal must be clean and *dry*. A thin wash of the 90% fused borax 10% sodium fluoride flux in water-free alcohol helps in the flowing of the metal.

Carbon Arc

A copper backing bar is not as a rule necessary for *carbon arc welding* of the copper-silicon alloys in thicknesses of $^1/_8$ in. or thicker. Sheets $^3/_{16}$ in. and thicker are beveled 45° for each edge in preparation for butt welds to be made without a backer.

Preheat is not always necessary though it is often desirable if there is any likelihood of the presence of moisture. In this case the preheat temperature should be well above the boiling point of the water; 250 to 300°F. is usually satisfactory.

The *carbon arc* has been used for the fusion welding of the copper-silicon alloys more than any other method. The use of a small, clear-surfaced weld pool helps in the control of the weld metal. The use of a relatively small-diameter, sharp-pointed carbon electrode is a further help. Current values vary from 70 amp. in an unbacked weld using a $^1/_8$-in. diameter copper-silicon filler rod melted at 1 in. of rod per inch of weld to 140 amp. for the same rod in a closely backed-up weld. A $^1/_4$-in. diameter welding rod may be melted with current values from 220 to 300 amp. depending upon the supporting surface.

The Group 4 copper-silicon sheets are readily *resistance spot and seam* welded. The optimum current values are slightly higher than the currents used for steel of the same thickness, made so by a shorter heat-on time. The metal being very fluid when molten should not be subject to a pressure as high as that commonly used for steel and it should be carefully controlled. With correct procedure, the full strength of the annealed metal is readily obtained.

CUPRO-NICKELS, GROUP 5

General.—The welding characteristics of the 70–30 cupro-nickel, Group 5, are not unlike those of Monel metal. Hence much of the data given in Chapter 24 is applicable to this group of alloys. In general, these alloys are readily welded by the oxyacetylene torch,[35] the metal arc, using covered electrodes, or resistance welding methods.

The four sources of trouble to be overcome in the welding of the Group 5 alloys are (*a*) the refractory, unfluxable nature of the nickel oxide which causes the metal to freeze with a rough, cinder-like surface, (*b*) the tendency of the metal to take up gas when molten and reject same on freezing thus

causing porosity, (*c*) the tendency to red shortness and (*d*) the danger of burning out the protective deoxidizers. The technique which will best avoid these difficulties calls for starting with clean metal, covering base metal and welding rod with flux to forestall oxidation during the heating-up and welding operations, the use of lightly clamped jigs for holding the metal in position for welding and a torch adjustment to give a soft, slightly reducing flame in gas welding or a heavy flux coating for metal arc welding.

The 70–30 cupro-nickel, 9W, bare welding rod has sufficient deoxidizer, as manganese or silicon, to protect the metal during the *gas-welding* process provided a soft flame[35] is used and the metal melted and allowed to solidify quickly with a minimum agitation. A few hundredths per cent of silicon in the welding rod will provide a film of liquid glass on the surfaces of the molten weld pool which will keep the torch gases from dissolving in the metal. Once started, the weld should be run continuously to its completion. The welding rod should be kept within the protection of the flame—not withdrawn into the air periodically for fluxing or slowing the fusion rate as is done with bronze rods.

The cupro-nickels of Group 5 are readily *silver brazed* with the SW alloys and *bronze welded* with the yellow bronzes, 5W. Excellent connections are made by either method with the usual technique.

Metal arc.—A heavy flux coating on the metal arc electrodes of this alloy is essential to the securing of sound, strong, ductile weld metal by this method. Methods of *carbon arc* welding have not been published.

Resistance welds.—The Group 5 alloys are very readily resistance welded, rating among the best of the copper alloys for this purpose.[22]

ALUMINUM BRONZES, GROUP 6 AND BERYLLIUM COPPER, GROUP 7

Remarks.—The aluminum oxide and the beryllium oxide are both very refractory, closely clinging and difficult to flux. Hence, *oxyacetylene welding* is difficult and *not generally commercially practicable. Silver brazing* can, however, be accomplished with a flux high in a fluoride constituent. *Resistance spot and seam welding* is also possible on sheet metal.[22]

The *metal arc* method with coated aluminum bronze electrodes is given first place, as, with the present commercial coatings high in fluorides, sound, strong welds are made. The operator should be cautioned against continuous breathing of the fumes while welding and good ventilation should be provided when the welding is being done in close quarters. These electrodes are used with a short arc, comparatively low d.c. in reversed polarity. They are unsatisfactory for use with an a.c. arc.[37]

In making aluminum bronze overlaps on *steel* with the flux-coated electrodes, the base metal is ground bright but no preheat is required. A weaving motion is used to make a bead $1/2$ to 1 in. wide. The arc is kept on the bronze as it is very undesirable to fuse the steel and bring particles of steel up into the bronze deposit. The successful application of aluminum bronze to cast iron calls for a careful preparation of the base metal to eliminate scale, grease and graphite, a moderate preheat of 250 to 300°F. and the lowest workable current. A *long carbon arc* with a bare or lightly

coated welding rod often makes the most satisfactory procedure for such purpose.[37]

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CHAPTER 23

ALUMINUM AND ALUMINUM ALLOYS*

Gas Welding, Metal Arc Welding, Atomic Hydrogen Welding, Brazing, Welding Castings, Inspection and Specifications, Resistance Welding, Characteristics of Welds in the Aluminum Alloys.

MOST of the common commercial welding methods have been adapted to joining aluminum and aluminum alloys. Correct application of these methods involves an understanding of the technique required to produce good results. Economical design of welded parts requires some knowledge of the physical and metallurgical properties of the materials. This chapter proposes to outline the essential characteristics of equipment and technique required to make welds and to incorporate established design and constructional details that have been proved to be successful in practice.

Aluminum and aluminum alloys are welded with the gas torch, metallic arc and the automatic or manual carbon arc. Resistance welding in the form of spot, seam or butt welding is also done. The relatively high thermal conductivity, expansivity and high electrical conductivity of aluminum require a welding technique that is peculiar to the material and is described as follows:

I. GAS WELDING

The commonly used gas processes for welding aluminum and aluminum alloys are oxy-hydrogen and oxyacetylene. Equally good results from the standpoint of soundness, strength, speed and appearance are obtained with either process. Standard equipment in the way of torches, hose and regulators is suitable for welding such materials. Some work has also been accomplished with oxy-natural gas and oxy-propane derivatives, and while good soundness and strength have been obtained in such welds, the use of these gases does not appear to be economical because of the comparatively low rate of welding.

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Flux

When gas welding aluminum, it is important that a suitable flux be used to remove the oxide coating which forms on the surface of all aluminum alloys in the atmosphere. This oxide coating does not melt at the welding temperatures and will prevent smooth coalescence of the weld metal unless a flux is provided that will melt somewhat below the welding temperature and which breaks down the surface skin of oxide, permitting the liquid metal from the welding rod to flow into the molten parent material. A number of good fluxes are available. These are applied either dry or by mixing with water to the consistency of a thick paste.

Practically all aluminum welding fluxes contain chlorides, fluorides and sulphates. Residual deposits on the joints after welding will, in the presence of moisture, attack the base metal. Thorough cleaning is especially necessary on parts that are to be painted, as the presence of flux will lift the paint coatings over the welds. Several methods, depending on the size and shape of the parts, are used for this purpose. If the part can be immersed immediately after welding and both surfaces are accessible to a brush, the cleaning can be done with a fiber brush in boiling water. Large chemical tanks cannot be immersed conveniently and are cleaned by scrubbing the joints with a brush and rinsing with a stream of fresh water.

Parts such as airplane gasoline tanks, beer barrels and enclosed vessels usually have the joints located so that mechanical loosening of the flux deposit is not feasible. In such cases an acid dip is used and the part immersed so that the acid contacts both the inside and the outside. Immersion in cold 10% H_2SO_4 for 30 min. or in 5% H_2SO_4 held at 150°F. for 5 to 10 min. is frequently used for flux removal. Immersion in 10 to 50% HNO_3 for 10 to 20 min. is also used. In either case, rinsing in hot or cold water after the acid dip must be accomplished. A corrosion inhibitor in the form of 5% sodium or potassium dichromate is sometimes added to the rinse water and has a beneficial effect, particularly on gasoline tankage.

The efficiency of the cleaning operations can be checked with an acidified solution of 10% silver nitrate. This is done by applying a few drops of distilled water to the surface where the presence of welding flux is suspected. After a few moments, enough of the flux will go into solution in the water so that if a drop or two are collected and in turn dropped into the silver nitrate solution a white precipitate will be formed provided flux was present on the part. If the solution remains colorless it can be assumed that cleaning operations have been adequate.

Filler Metal

The proper choice of filler material for gas welding is important, particularly when joining alloys with comparatively large amounts of alloying constituent. Commercially pure aluminum, and metal of higher purity, are generally welded with the same grade of metal as the parent material. The same practice is satisfactory for the aluminum-manganese alloys. In welding the aluminum-magnesium alloys or aluminum-silicon-magnesium alloys, a filler rod containing approximately 95% aluminum and 5% silicon is generally used. This rod has a substantially lower melting

point than pure aluminum, and permits the dissipation of some of the stress set up by solidification shrinkage and the thermal contraction which occurs in the weld zone as it cools. Cracks in the weld and the transition zone, on parts that are welded in jigs to hold proper alignment, can be minimized by using this rod.

Finish

It is necessary to finish the weld bead on some parts where sanitation or appearance is important. On equipment for handling food or chemicals where a smooth, easily cleaned surface is desired, butt welds are dressed by hammering. This is done by chipping the edge of the weld bead flush with the surface of the parent metal, and then hammering the balance of the bead over a backup block with blows heavy enough to work the metal through the entire cross-section. This practice differs somewhat from the conventional peening process used on welds in other metals, in that more than the surface of the weld is worked by the hammering.

Finishing fillet and corner welds is done by grinding. The tendency to load up the conventional grinding wheels with aluminum can be overcome by using felt base wheels. The grinding compound is applied by rolling the edge of the wheel in glue, followed by rolling in abrasive compound graded in fineness from 60 to 200, depending on the surface required on the finished part. Buffing and color buffing operations are performed on welds in the same manner as on the parent metal.

Distortion

Because the aluminum alloys have a relatively high coefficient of thermal expansion compared to most weldable metals, it is desirable to minimize buckling and distortion from the welding heat by proper design and preparation of joints. On parts with flat sides minimum distortion is obtained when the weld is placed on an edge or a corner. Designs with crowned surfaces are better than flat surfaces from this standpoint. It is important to provide the most advantageous weld location in the original design. The location of welded seams or fittings in flat areas should be avoided. For parts subjected to pressure the most economical design is for butt welding. This is true on cylindrical vessels even though minimum distortion is obtained if the heads are reversed and edge welded in place.

In addition to controlling buckling, it is essential that the sheet edges be properly prepared if sound welds of maximum strength are to be attained. Edge preparation for various thicknesses of material is shown in Fig. 1. Proper alignment of the abutting edges is important in controlling distortion. This can best be done by tack welding at frequent intervals along the seam. On material up to $^1/_{16}$ in. thick such tacks are placed from 1 in. to 2 in. apart, depending on the length of the seam. This spacing can be increased proportionately up to a tack spacing of about 10 in. on material $^1/_2$ in. thick and heavier.

The use of cold packs in the form of water-soaked rags or carbon backup blocks to control distortion is only of assistance in isolated cases when gas welding the aluminum alloys. Because of the thermal conductivity of the metal, heat is removed from the weld zone by the above expedients so

rapidly as to interfere with the molten metal. This rapid cooling must be balanced by an increase in the flame size, with a consequent tendency to produce distortion of the parts.

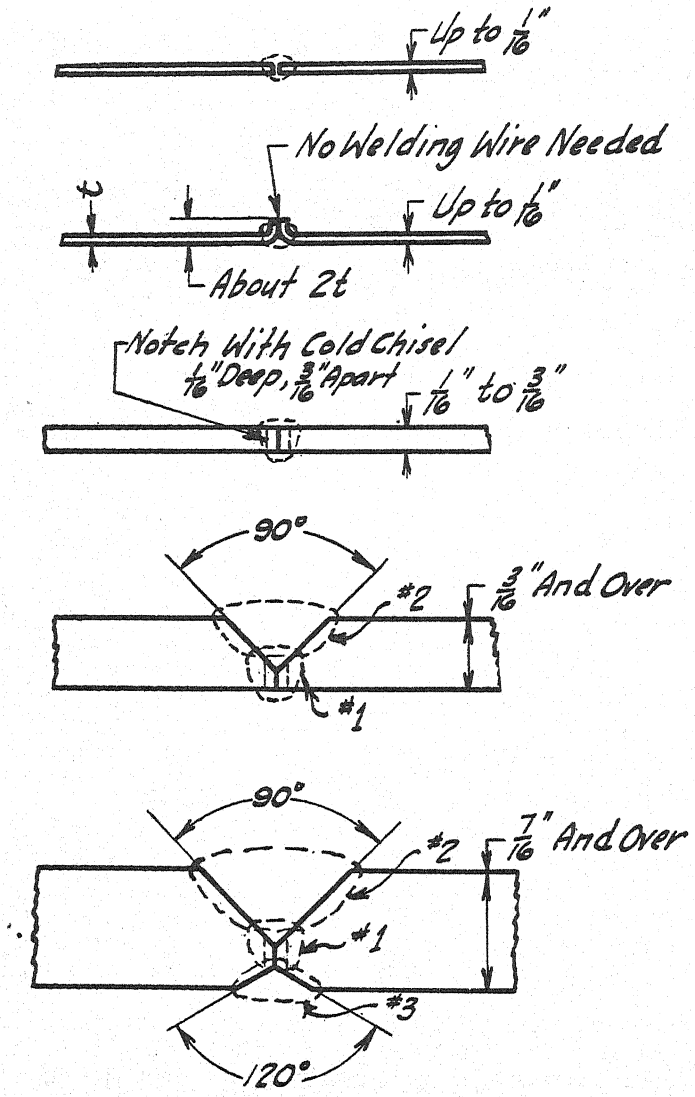


Fig. 1—Preparation of Edges for Gas Welding

II. ARC WELDING

Aluminum and the aluminum alloys can be welded with the metallic arc. This process has the advantage that the highly concentrated heated zone obtained with the arc prevents excessive expansion of the parts being welded with consequent lessening of distortion. In addition, the preparation of the joints for welding is simpler and the rate of welding is faster.

Because of the relative difficulty of controlling the arc, however, it is not practicable to butt weld material lighter than 0.081 in. thick in the shop, or fillet weld joints on plate lighter than $^1/_8$ in. thick. While arc-welded joints are equal in strength to gas-welded joints it is difficult to obtain liquid or gas-tight joints in material lighter than $^1/_4$ in. thick.

Metallic arc welds can be made with the standard d.c. motor generator sets used for welding other metals. The proper polarity to be used should be determined by trial on the joints to be made. The capacity of the equipment and the electrode size are determined by the thickness of the material to be welded. Table 1 provides approximate machine settings and electrode sizes for welding various thicknesses of aluminum.

Table 1—Electrode Size and Machine Setting for Metallic Arc Welding Aluminum

Metal Thickness, In.	Electrode Diam., In.	Approx. Current, Amp.	No. of Weld Passes		Electrode Consumption			
			Butt	Lap & Fillets	Butt Lb./100 Ft.	Lap Lb./100 Ft.	Fillets Lb./100 Ft.	Electrodes/ Lb.
0.081	$^1/_8$	60	1	1	4.7	5.3	6.3	32
0.101	$^1/_8$	70	1	1	5.0	5.7	6.3	32
0.125	$^1/_8$	80	1	1	5.7	6.25	6.3	32
0.156	$^1/_8$	100	1	1	6.3	6.5	6.5	32
0.187	$^5/_{32}$	125	1	1	8.7	9.0	9.0	23
0.250	$^3/_{16}$	160	1	1	12.0	12.0	12.0	17
0.375	$^3/_{16}$ for Laps and Fillets $^1/_4$ for Butts	200	2	3	25	29	35	17
0.500	$^3/_{16}$ for Laps and Fillets $^1/_4$ for Butts	300	3	3	35	35	35	17

Flux

Unless a suitable flux is provided, the surface oxide present on the electrode core wire and the parent material will prevent coalescence of the weld metal. Consequently, successful results are most easily obtained by using a coated electrode on which a heavy coating is provided that functions both to remove the surface oxide on the metal and to stabilize the arc. As the 95% aluminum-5% silicon alloy provides superior fluidity at the welding temperatures, this alloy is used for the filler material in almost all of the commercially available electrodes.

Edge Preparation

The preparation of butt joints for metallic arc welding is somewhat simpler than that required for gas welding. Because of the ease with which

complete penetration can be obtained no edge preparation is required on material up to 1/4 in. thick. Heavier materials should be partially beveled to within 1/4 in. of the bottom of the section. Such preparation can sometimes be dispensed with on material from 1/4 in. to 1/2 in. thick if a weld deposit can be laid down from both sides of the section. In welding from one side only, it is desirable to confine the rootpass by placing a copper backup strip below the joint. This strip should be provided with a cylindrical groove about 1/2 in. wide by 1/16 in. deep directly below the weld.

Carbon Arc

Wider use of the carbon arc for welding aluminum has been apparent recently. The reason for this is that sound welds, comparable in structure and appearance to gas welds, can be made with substantially less distortion in the parts. Both manual and automatic methods are used and the automatic carbon arc is the only automatic arc method that has found production use for joining the aluminum alloys.

The technique for manual carbon arc welding is similar to that used for other metals. A flux-coated rod is used to supply filler material. Improved welding speed and appearance will result with a filler rod covered with a thinner coating than the standard metallic arc electrode, although the latter are frequently used for filler material on this class of work. Material 1/16 in. thick up to about 3/8 in. thick is welded commercially. Joint preparation is similar to that used for gas welding. Rod size and welding current as shown in Table 1 for metallic arc welding are also approximately correct for carbon arc welding.

This process has been adapted to automatic equipment where the quantity of welding justifies the initial cost. Such installations have been used commercially for assembling alloy tank cars, and increased use of the process is anticipated on welded tankage for chemicals, gasoline breweries and other applications of a similar nature.

Table 2—Automatic Carbon Arc Welding Aluminum Alloys

Thickness, In.	Current, Amp.	Arc Voltage	Rod Size, In.	Wire Speed, In./Min.	Rod Consumption per 100 Ft. Weld, Lbs.	Flux Consumption per 100 Ft. Weld, Lbs.	Welding Speed, In./Min.
0.188	310	35	5/32	16.8	2.5	17	16
0.250	360	36	5/32	20.3	3.68	21	14
0.312	380	38	1/4	9.6	4.78	26	12.3
0.375	390	38	1/4	10.2	5.0	28	12
0.500	410	39	1/4	9.3	7.8	51	7.1

Standard automatic equipment with a superimposed a.c. field to control the arc is used for this work. Data on machine settings, filler material and flux are shown in Table 2. This information applies to butt joints and represents average conditions. Some adjustment of the variables

shown must necessarily be accomplished on individual jobs, although the information is suitable for all of the weldable aluminum alloys.

In application of the process no edge preparation is required on butt joints other than fitting the parts so that the abutting edges meet uniformly along a straight line. Backing up the weld is essential and this is usually provided by a $^1/_4$-in. thick or thicker copper bar with a $^1/_{16}$-in. deep by $^3/_8$-in. wide groove placed directly below the joint. Metallic arc tack welds or clamping devices are used to hold the edges in alignment.

Powdered flux is fed on the joint automatically and there are several good fluxes available for this purpose. Filler wire is also fed automatically. The same filler alloys used for gas welding can be applied with this method, although hard-drawn rather than annealed wire will feed more uniformly through the wire feeder. Commercially pure aluminum and aluminum-manganese alloy are welded with 99% aluminum wire and other alloys with 5% Si-95% Al wire. The diameter depends on the thickness welded, as shown in Table 2.

The same precautions for the removal of welding flux should be followed as are outlined for gas welding. Weld dressing after cleaning can also be handled in the same manner.

III. ATOMIC HYDROGEN WELDING

The atomic hydrogen welding method can also be used for assembling aluminum parts. In this process a stream of hydrogen is directed into an arc drawn between two tungsten electrodes. Good results have been obtained from the standpoint of soundness and strength of welds in the aluminum alloys with both manual and automatic atomic hydrogen welding equipment.

As this process involves an arc that is formed between electrodes in a hand torch it is possible to control the heated zone on the parts being welded by moving the torch away from or toward the work. Filler rod is applied manually in much the same manner as when gas welding. Consequently, the process combines some of the flexibility of the gas welding operation with the concentrated heated zone of the metal or carbon arc. It is possible with the atomic hydrogen to make fillet or lap welds on an alloy such as 52S with little difficulty from cracking or overheating of the parts being welded.

Welding with the atomic hydrogen is usually performed with standard gas welding flux. Both sides of the joint are painted with a water mixture of the flux and the filler rod is dipped in the mixture prior to welding. The technique of making the joint resembles gas welding and requires some practice in order that the operator becomes adept at holding the arc and controlling the weld puddle. Butt welds can be made in material from $^1/_{16}$ in. up to $^3/_8$ in. thick and heavier. Approximate values for current and wire sizes are shown in Table 2A.

The action of the welding heat on the flux is more severe than when gas welding, and after the joint solidifies a heavier scum than usual is presented on the surface. This will interfere with laying down subsequent weld

Table 2A—Approximate Machine Settings—Atomic Hydrogen Welding

Thickness, In.	Current, Amp.	Hydrogen Pressure, Psi.	Filler Wire Diam., In.
0.064	10	7	1/8
0.081	15	7	5/32
0.101	21	8	5/32
0.125	27	8	3/16
0.187	33	11	3/16
0.250	39	14	3/16
0.375	45	14	1/4

beads and removal of the surface deposit is usually required on parts where the thickness requires more than one weld bead to make the joint.

The preparation of the joints prior to welding and the removal of welding flux after welding are accomplished by the same methods already described for use on gas welded joints.

IV. BRAZING

Alloys and Materials

Proper flux, filler materials and technique have been developed for brazing commercially pure aluminum, aluminum-manganese alloy and the magnesium-silicide aluminum alloys which are heat treated to obtain high strength. Technique and filler materials have not yet been developed that will permit the brazing of the aluminum-copper alloys. Filler material is supplied as a wire shim or sheet washer, depending on the geometry of the joints. A duplex brazing material consisting of an aluminum-manganese core with an integral coating of filler material is also used. This material has been designated as No. 1 brazing sheet when coated on one side and No. 2 brazing sheet when coated on both sides. The use of this sheet makes it possible to form and assemble parts, apply flux and braze without the placing of additional filler material at the joints.

Fluxes must be used in all aluminum brazing operations to break up the oxide coating so that the filler material will wet the adjacent surfaces of a joint. The flux is usually mixed in a ratio of two parts of flux to one of distilled water and applied to the part by brushing, spraying or dipping.

Furnace Equipment—Time and Temperature

Brazing operations are performed in standard types of furnace equipment. Temperature regulation within ±5°F. of the nominal temperature is necessary to get consistent results. This requires automatic temperature control. For most parts circulation of the furnace atmosphere is not essential to the brazing operation but is a desirable feature in furnace construction in that it reduces the heating time and results in more uniform distribution of temperature in the furnace. If the parts to be brazed are subdivided into passages too small in area to permit uniform temperature rise by the natural convection currents in the furnace, forced circulation is absolutely essential. Both gas-fired and electrically heated furnaces have

been used, as well as batch and continuous types for handling the load. The furnace design should be based on an operating range of 1000 to 1200°F.

The total time brazed parts are exposed to the furnace temperature depends on the thickness of the parts. Experience indicates that furnace-brazed parts can be made from 0.006 in. thick up to 1/2 in. thick. Material 0.006 in. thick will reach brazing temperature in a few minutes, while it requires 40 to 45 min. for 1/2-in. thick material to reach temperature. A period of from 2 to 6 min. after the metal reaches the brazing temperature is required to melt the filler material and flow it into the joints. Time for any specific job is determined by trial. In this connection it should be noted that because of the varying rate of temperature rise it is not good practice to design a part so that a large range of thickness occurs in the various pieces in the parts.

The brazing temperature is adjusted to suit the alloy being brazed. In the case of aluminum-manganese parts a temperature between 1160 to 1185°F. is used. Magnesium-silicide aluminum alloys are brazed from 1060 to 1090°F. The correct temperature for a specific job is determined by trial and will depend on the design of the part and the size of fillets required. Larger fillets are obtained at the upper end of the temperature range. In determining the correct temperature it is desirable to measure actual load temperatures by attaching a thermocouple to one of the parts to be brazed.

Torch Brazing

Torch brazing differs from furnace brazing in that the heat is applied locally with a welding torch. Oxy-hydrogen, oxyacetylene, or oxy-natural gas flames have been used for this purpose. The brazing flux is mixed with water and applied to the filler rod by dipping. Heat is applied to the part with a flame until the temperature reaches a point where the flux and the filler material melt and wet the surface of the parent material with little or no melting in the parent part. The process resembles gas welding except that the filler material is more fluid and will flow into a lap joint. The speed of making the joint is also more rapid.

Performance of Brazed Joints

The temperature reached in furnace brazing any of the common alloys is above the recrystallization temperature and, consequently, the parts are annealed by the brazing operation. The strength of the parent material and the design of such parts should be based on the annealed strength of the alloy.

In brazing heat-treatable alloys it is sometimes possible to air or water quench the part after removal from the brazing furnace. These parts are subsequently artificially aged to the "T" temper. The same results can be attained by solution heat treating and quenching the part in a separate operation after the brazing operation.

The strength of torch-brazed parts is approximately the same as if the parts were assembled by gas welding. The heat is applied locally and anneals the metal in the neighborhood of the joint. The amount of anneal-

ing that takes place depends on the amount of brazing done. In this case the strength of torch-brazed parts should be determined by trial.

There is not yet sufficient experience to establish definitely the corrosion resistance of brazed joints. However, sufficient testing has been accomplished in salt spray, atmospheric and other types of exposure to indicate that the corrosion resistance is comparable to the resistance of welded joints in the same alloy. If the exposure conditions are such that the parent material would need protective paint coatings to resist service conditions, brazed joints in the parts should receive the same protective treatment. Where the aluminum alloy can be used bare, it is quite likely that brazed joints will stand up satisfactorily.

Flux Removal

It is always necessary to clean the part after the brazing operation. Many parts can be immersed in boiling water before cooling from the brazing temperature. This will remove the major portion of the flux. If such a quench distorts the part it should be allowed to cool in air and then immersed in boiling water.

This is followed by a dip in concentrated nitric acid for 10 to 15 min. The acid is removed from the part with a water rinse, preferably in boiling water, in order to accelerate the drying of the part. An alternative cleaning method is to dip the part in a 5% sulphuric acid solution held at 150°F. for from 5 to 10 min. This in turn is followed by a water rinse.

On brazed parts with thin sections (0.010 in. and lighter) and on parts where the maximum corrosion resistance is important, the part should be cleaned by immersing in hot water followed by a dip in 10% nitric-10% sodium dichromate solution held at 150°F. from 10 to 30 min. This in turn is followed by a hot water rinse. This solution rapidly removes flux without staining the metal and can tolerate a large contamination of flux salts without accelerating etching or pitting of the parts. If this is followed by a dip in 0.01 to 0.1% sodium dichromate the corrosion resistance of thin sections is better than when the parts are cleaned in sulphuric acid.

V. WELDING CASTINGS

In general, the welding of aluminum alloy castings requires techniques similar to those used on aluminum sheet and wrought sections. The susceptibility of many castings to thermal strains and cracks, because of their intricate design and varying section thickness, should be carefully considered. In addition, many castings in highly stressed structures depend on heat treatment for their strength, and welding tends to destroy the effect of such initial heat treatments. Unless satisfactory facilities for reheat treatment are available, the welding of such heat-treated castings is not recommended.

Preparation

When a broken aluminum casting is to be welded, it should first be cleaned carefully with a wire brush and gasoline to remove every trace of oil, grease and dirt. Unless the casting has a very heavy cross-section, it is

not necessary to tool the crack or cut out a vee as this can generally be accomplished by means of the torch and puddling iron. It is necessary, however, that the stock surrounding the defect be completely melted or cut away before proceeding with the weld. If a piece is broken out, it should be held in correct position by light iron bars and appropriate clamps. The clamps should be so attached that the casting will not be stressed during heating.

Preheating

If the casting is large or has intricate sections, it should be preheated to between 500 to 700°F. slowly and uniformly in a suitable furnace prior to welding. If the casting is small, or if the weld is near the edge and in a thin-walled section, the casting may be preheated in the region of the weld by means of a torch flame. Cast aluminum should be heated slowly to avoid cracking in the section of the casting nearest the flame.

Broken pieces should be tack welded into place as soon as the casting has been preheated. The actual welding of the piece should commence at the middle of the break, and welding should be done toward the ends. The welding rod must be melted by the torch, as the heat of the molten metal of the weld is not sufficient to melt it. When the weld is finished, the excess molten metal should be scraped off with a puddling iron, and the casting allowed to cool slowly.

Technique

Holes in castings are welded in much the same manner as are cracked and broken castings. It is necessary to melt away or cut away the sides of the hole in order to remove all pockets and to permit proper manipulation of the torch.

For welding ordinary castings, a 95% aluminum-5% silicon or 93% aluminum-4% copper-3% silicon welding rod is generally used. However, in the case of heat-treated alloy castings it is best to use a welding rod of the same alloy as the casting.

A flux should be used when welding aluminum castings. Puddling alone will merely break up the oxide film and leave it incorporated in the weld, while fluxing will cause the oxide particles to rise to the surface so that a clean, sound weld will result. It is important that the added metal be completely melted, and the molten metal thoroughly worked with the end of the welding rod or with a puddling iron. Thus, the flux and oxide are worked to the surface of the molten metal, and there is very little danger of contaminating the weld metal with particles of flux or other foreign inclusions.

In the welding of large castings in which the area to be welded is sufficiently large and easily accessible, the welding rod is often dispensed with, and molten metal added directly from a small ladle. By this practice the amount of porosity and oxide in the weld is reduced to a minimum, the tendency for burning in the surrounding areas is lessened, and the welder is using metal of the same analysis as the casting.

Poured welds are recommended for filling large holes and cracks. To accomplish this a form or jig of fire clay, plaster of Paris or metal is fitted

around the hole or crack. After the casting has been preheated in a suitable furnace, the flux is brushed on the faces to be welded and the metal is brought up to the proper temperature by means of a torch. Molten metal, at not over 1300°F., is poured into the weld. The flux and absorbed oxide will immediately float to the surface and can be skimmed off.

Carbon Arc

The metallic or carbon arc can also be used for the welding of castings. Of the two methods, the carbon arc is to be preferred as it produces welds freer of oxide and porosity. Even with the carbon arc method, castings in some cases must be preheated to eliminate thermal strains. The use of rods carefully coated with flux and the control of welding current are essential for good arc welds.

VI. INSPECTION AND SPECIFICATIONS

Means of controlling quality of welded joints in the aluminum alloys are based on the same principles in practice on ferrous materials, although they differ in detail and specified values. The field of written specifications for procedure and materials is not completely covered. Gas welding on pressure vessels, however, is now accomplished under controlled conditions which are described as follows.

Qualification of welding operators may be accomplished by butt welding two $^3/_8$ in. x 9 in. x 17 in. aluminum-manganese plates. Methods of testing the weld vary. The simplest procedure consists of a 180° guided bend test made over a $1^1/_2$-in. mandrel on gas welds, and a $2^1/_2$-in. mandrel on metallic arc welds. In some cases reduced section tensile tests are made and a minimum of 14,000 psi. has been established. Where free bend tests are accomplished a minimum elongation of 20% is used. Soundness as determined by nick break tests is usually judged on the same standards shown in the A.S.M.E. Code for Unfired Pressure Vessels.

Qualification of the welding process is carried out in a similar manner

Table 3—Specifications

Title	Origin and Number
Welding Procedure for Certification of Welders	Army Air Corps—20013B
Qualification Tests for Metal Arc Welders	Navy—Appendix VII, Part E, Section E-1
Qualification Tests for Gas Welders	Navy—Appendix VII, Part E, Section E-2
Fusion Welded Pressure Vessels, Storage Tanks and Vacuum Tanks Constructed from Aluminum Plate	Linde Air Products Co. PV No. 4
Welding Aluminum-Manganese Plate for Unfired Pressure Vessels	Aluminum Company of America
Welding Aluminum and Aluminum Alloys	Navy—Appendix VII, Part C, Section C-9
Gas Welding Aluminum and Aluminum Alloys	Naval Aircraft Factory PW2a
Flux, Welding, for Aluminum and Aluminum Alloys	Navy—51F6 Army Air Corps 11313
Rods, Welding, Non-ferrous, for Gas and Carbon Arc Welding	Navy—46R1 Federal QQ-R-571

except that this qualification need be done only once and not repeated periodically. The qualification of welding operators is repeated when the welding operator has not been engaged in the actual use of the welding process for which he was qualified for a period of three months or more or when in the opinion of an Inspector his work is of doubtful or uncertain quality. (Qualification on the above basis permits the operator to weld any of the weldable alloys up to metal $^3/_4$ in. thick.) Accepted practice has not yet established qualification procedures for metal heavier than $^3/_4$ in.

Detail specifications for various types of work have been issued as listed in Table 3. Duplication of the material shown in these specifications is too voluminous to include here.

VII. ELECTRIC RESISTANCE WELDING

All of the commercial aluminum alloys which are produced in the form of sheet and extrusions, may be spot welded provided the thicknesses involved are not too great. The provision of proper equipment for making the welds, the preparation of the surface of the material for welding and the use of correct machine settings are necessary for producing satisfactory welds.

Aluminum and aluminum alloys have comparatively high thermal and electrical conductivity, and in order to make spot welds, high values of welding current and relatively short welding times are necessary. A further factor which influences the choice of equipment for spot welding aluminum is the rapid softening of the material at the welding temperature which necessitates a slight movement of the welding electrode into the material being welded. While this movement is small it must take place in a very short time, perhaps 0.002 to 0.005 second, and as a consequence, considerable acceleration of the welding electrode assembly is necessary if contact is to be maintained between the welding electrode and the material welded. For this reason, the moving electrode system should possess low inertia and should be so guided as to minimize friction.

A.C. Spot Welding

One method in wide use is the alternating current method wherein the high welding current is obtained from the secondary of a welding transformer having a turn ratio from 20:1 up to 100:1. The primary of the welding transformer is usually connected to either 220 or 440-v., 60-cycle power supply, and suitable means are interposed between the power supply and the welding transformer to provide a range in time of application of welding current from one cycle up to thirty cycles. The secondary current required varies with the thickness of the material welded as listed in Table 4.

In order to properly adjust the current for intermediate thicknesses of materials a means of adjusting the current in steps of approximately 1000 amp. is usually provided. Taps either on the primary of the welding transformer or a separate auto-transformer may be used. Another method commonly used is to delay the ignition of the electronic tubes controlling the welding time. This results in a reduction of the welding current and

Table 4—Table of Machine Settings for Spot Welding Aluminum Alloys

Gage		Time,	Current,	Tip Pressure, Lb.	
B&S No.	In.	Cycles	Amp.	Min.	Max.
26	0.016	4	14,000	200	400
24	0.020	6	16,000	300	500
22	0.025	6	17,000	300	500
20	0.032	8	18,000	400	600
18	0.040	8	20,000	400	600
16	0.051	10	22,000	500	700
14	0.064	10	24,000	500	700
12	0.081	12	28,000	600	800
10	0.102	12	32,000	800	1000
8	0.128	15	35,000	800	1200

a change in the wave shape of the welding current and may be used to reduce the current from the maximum output of the welding machine down to about 50% of this output. Where further reduction in welding current is required, a series parallel switch is provided on the welding transformer primary to permit adjustment of the current down to 25% of the maximum current output, which is usually sufficient to cover the normal range of material thicknesses.

The welding pressure may be obtained either from a cam and spring mechanism, a pneumatic cylinder or a hydraulic cylinder. Pneumatic operation is preferred since most plants have compressed air systems and the welding pressure may be conveniently adjusted to the desired value. The pressure required on alternating current welding machines is given in Table 4.

The welding time on a.c. welding machines is controlled by means of a switch in the supply line to the welding transformer primary. Both mechanically operated and magnetically operated welding contactors have been used for this purpose with good results. Such a device should control the welding time to the values listed in Table 4, with an accuracy of plus or minus one cycle. Improved welding results are obtained when the devices are adjusted so as to close the circuit at a definite point in the voltage wave and to open the circuit when the welding current passes through zero, although some variation from this ideal condition is permissible for welding most of the aluminum alloys.

Electronic equipment to control the duration of welding current is widely used with alternating current aluminum welding machines. When such equipment is provided with means to start the flow of current in synchronism with the supply voltage, the appearance of the welds and the consistency of weld strength are superior to those obtained with less precise timing equipment. Electronic timing equipment which may be used to control the magnitude as well as the duration of welding current is often used and provides a stepless adjustment of the welding heat.

Current Demand

One of the chief objections to alternating current spot-welding machines is that the high currents for welding aluminum place a very high electrical demand upon the system supplying the welding machine. This current

demand is of intermittent nature, single-phase, and of very low power factor, and may cause disturbances with other electrical consuming equipment such as the blinking of lights. This condition may be alleviated to a large extent by the installation of static condensers in series with the primary of the welding transformer. The manufacturer of the welding equipment should be consulted in connection with the proper size and number of condensers required.

Energy Storage Method

The electrical demand for spot welding aluminum may be reduced even further by the use of energy storage welding equipment, two types of which are available. The magnetic energy storage type of welding machine stores the welding energy in an inductor transformer by establishing a direct current of from 100 to 400 amp. in the primary winding of this transformer. Upon the interruption of this current by a magnetic contactor a high value of current is established in the secondary circuit, and through the work being welded. This current drops to a low value in from 0.01 to 0.05 sec. Equipment using this process is also provided with an electrode pressure system which permits the welding pressure to be varied during the welding operation. The combination of the short time welding current impulse, together with the varying pressure, results in welds of excellent appearance and of very sound structure.

The direct current used in the primary of the inductor transformer is usually obtained by rectifying a three-phase 440 or 220-v. shop supply. The maximum power demand for this type of equipment is about one-tenth that of alternating current equipment, welding the same thickness of material, as the energy is obtained by drawing a lower amount of power for a much longer time.

The condenser energy storage equipment utilizes static condensers to store the energy used for welding. The three-phase shop power is stepped up in voltage and rectified so as to charge the condensers to a voltage from 1000 to 3000 v. d.c. When this bank of charged condensers is connected to the primary of the special welding transformer an impulse of welding current rising rapidly to its maximum value and decreasing again to zero somewhat slower, is obtained. When welding with this equipment a constant high value of welding pressure is usually used. In some cases a higher pressure is used at the end of the weld to provide a forging action on the solidified weld metal. Welds produced on this type of equipment are of excellent appearance and of very sound structure. The maximum demand on the power system for this energy storage system is also about one-tenth that required for a.c. welding equipment welding the same thickness of material.

With all of the above forms of welding equipment the power required for welding is dependent both upon the material welded and the throat area of the welding machine. In order to minimize the problem of obtaining power supply and to reduce the cost of the welding equipment, it is advisable to use a welding machine with the shortest length of arms and the minimum arm spacing compatible with the shape of work to be welded.

Table 4 shows the approximate welding current and welding pressure variation during welding with the above processes.

Electrodes

The proper choice of electrode shape and the maintenance of this shape in production is essential to obtain consistent spot welds on aluminum. The welding electrode serves as a means of conducting the welding current into the parts being welded, exerting sufficient pressure on the material to hold them in place while the weld is made, and of conducting the heat out of the parts welded to prevent the weld zone from reaching the outside surfaces of the material. At least one of the electrodes must be of such shape that a high concentration of current will be obtained in the weld. This electrode may be dome shaped with a 1 to 2-in. radius, or it may be conical with a 158 to 166° included cone angle. Another shape of tip often used with the energy storage welding processes consists of a truncated cone with a 160° to a 130° cone angle and a flat spot with a diameter equal to twice the thickness of the material welded, plus $^1/_8$ in. The electrode on the other side of the work may be of the same shape or a flat electrode may be used on one side of the work to obtain a surface with the minimum of electrode marking. These flat electrodes may be from $^5/_8$ in. to $1^1/_4$ in. in diameter, further increase in diameter resulting in no improvement in the appearance of the work welded.

Whether the dome or conical electrodes are used it is essential that they be made from a material having high hardness and high electrical and thermal conductivity. A number of copper alloys having hardnesses greater than Rockwell B-65, and electrical conductivities greater than 75% of that of pure copper, are used. Hard-drawn copper electrodes of conical or dome shape will not maintain their shape in production welding and their use is to be avoided. The truncated cone tips are often made from hard-drawn copper if the welding pressure used is not too great for the size of electrode used.

The electrodes must be of sufficient diameter to carry the welding currents used without undue heating. A $^5/_8$-in. diam. electrode is suitable for currents up to 35,000 amp. and a welding time of 15 cycles when the rate of welding is not more than 40 welds per minute. Where higher welding currents or greater welding speeds are used, $^7/_8$-in. diam. or $1^1/_4$-in. diam. electrodes should be used. For welding currents less than 20,000 amp. and welding times less than 8 cycles, $^1/_2$-in. diam. electrodes are satisfactory.

The electrodes must be water cooled by a stream directed against the end of the electrode water-cooling hole. This hole should extend to within $^3/_4$ in. of the welding face. A water flow of one or more gallons per minute should be maintained through the electrode.

With continued welding a coating of aluminum alloy forms over the face of the electrode. This aluminum alloy is of low electrical conductivity and continued welding with it on the electrode surface soon results in sticking of the electrodes to the work and melting of the surface of the material welded. This "pickup" may be removed by dressing the electrodes with a fine grade of abrasive cloth. In dressing dome shaped electrodes to remove "pickup," care should be taken to maintain the original electrode shape.

Where the truncated cone type of electrode is used, considerable care must be exercised to maintain exact parallelism of the upper and lower

electrode faces, and to maintain the diameter of the flat area constant.

On alternating current welders using domed or coned electrodes, the tips must be dressed to remove "pickup" after from 15 to 80 welds, depending upon the material welded. On energy storage equipment using the truncated cone type of electrodes, less "pickup" is obtained and from 60 to 300 welds may be made before cleaning of the electrodes is necessary. The tip cleaning operation requires from two to three seconds.

Preparation

Aluminum alloys 2S and 3S are usually received with fairly bright surfaces, and the only cleaning necessary for welding is to remove the grease, dust and oil from the area where the welds are to be made. Aluminum alloys 52S, 53S-W and 53S-T, 61S-W and 61S-T, 17S and 24S are characterized by a rather heavy oxide coating and while welding may sometimes be performed without removing this coating, better quality welds and more economical welding will result if both surfaces of the material are cleaned prior to welding. On alclad 17S-T and alclad 24S-T material, welds with better soundness can be obtained when the material has been cleaned. The surface of aluminum may be cleaned for spot welding mechanically with a fine grade of abrasive cloth, fine steel wool or a fine motor-driven scratch brush. In cleaning alclad material by a mechanical means, care must be taken not to remove the protective coating on the surface.

Where the parts are of such size that they may be dipped, a satisfactory cleaning procedure consists of dipping the parts for thirty seconds in 5% NaOH at 160°F., rinsing in cold fresh water, dipping for one minute in 50% HNO_3 at room temperature, rinsing in cold fresh water, rinsing in boiling water and drying. In some cases it will be necessary to repeat the sodium hydroxide and nitric acid dips to thoroughly clean the material. There are also a number of cleaning materials available commercially, especially designed for cleaning aluminum prior to spot welding, which are applied in accordance with the recommendations of the manufacturers of these materials.

Where the parts are too large to permit dipping, or where the parts are partially assembled, and there is a possibility of the above solutions getting into joints already made, the surfaces to be welded may be cleaned by an etching solution which is painted on with a brush, allowed to stand on the surface for thirty seconds and then sponged off with a wet cloth. One etch of this type may be prepared by mixing the following materials:

A. 2.9 lb. gum tragacanth
7.1 lb. denatured alcohol
8 lb. hot water

B. 10 lb. 30% hydrofluoric acid

The gum tragacanth is dissolved in the hot water. In some cases the use of alcohol is not necessary as the gum will go into solution in the water. Other grades of gum will not dissolve, and alcohol is added to accelerate solution. The 10 lb. of 30% HF is added to solution *A* to complete the preparation of the etch. Where the etch is to be used on oily stock the

addition of a wetting agent will improve the spreading action of the solution.

Shop Practices

In order to set up the welding machine to produce satisfactory spot welds, the production of sample welds is necessary. The machine settings given in Table 4 apply particularly to alternating current welding machines, and form a basis for making the initial trial welds. A series of welds should be made on sample stock of the same gage, alloy, surface condition and spot spacing as the job to be welded. This specimen is torn apart by driving a chisel in between the sheets and in between the welds or by a "peel" test. Each spot weld should pull a button* of diameter equal to twice the thickness of the material, plus $^1/_{16}$ in. If the spot diameter is too small it may be increased by increasing the welding current in steps of about 1000 amp. If expulsion of metal from the weld between the sheets is occurring on the welds, the welding pressure should be increased. If the outside surfaces of the sheet exhibit evidence of excessive darkening or surface melting, or of sticking to the electrodes after only one or two welds have been made, either the pressure should be increased or the current decreased.

Spot welds in aluminum alloys 17S and 24S and aluminum alloys alclad 17S and alclad 24S will not always pull buttons all the way through the sheet when the thickness of material is greater than 0.080 in. In these materials the weld is tested as above and the diameter of the fractured area determined. On alternating current welding machines little is to be gained by adjusting the welding time different from the values given in Table 4. On high-speed welding where soundness of the welds is not important, or where the material welded is 2S or 3S, the welding time may be decreased to as low as 60% of the values listed in Table 4, to prevent excessive heating of the electrode. Little effect on the size of the weld will be noted.

When welding unequal thicknesses of materials, the thickness of the material which is used against the domed or conical tip governs the machine setting and the diameter of the weld. If domed tips are used on both sides of the work, then the thinner sheet governs the machine setting and diameter of the weld. Where more than two thicknesses are welded, the setting is governed by the outside sheets using values of welding current and welding pressure slightly higher than normal. If expulsion of metal between the sheets cannot be entirely eliminated by changing the machine settings, a more thorough method of cleaning the material should be adopted. A light rub of the material with fine steel wool just before welding will often help this condition.

Spot welds in alclad 17S-T, alclad 24S-T and 24S-T, are subject to cracking if too high a value of welding current or too low a value of welding pressure is used, or if the material is not cleaned sufficiently. These cracks may be eliminated or reduced to some extent by using a larger radius on the domed electrodes or by dressing a small flat spot not greater than 2T + $^1/_{16}$ in. in diameter on the domed or cone tip (T equals thickness of material). This flat spot reduces the indentation of the electrode

* A circular piece of base metal.

into the sheet and results in maintaining more uniform pressure during the weld.

Strength of Welds

Spot welds are usually designed to carry shear loads. The strength of the welds will vary to a considerable extent with the alloy welded, the thickness of the material welded, and the machine settings used in making the welds. Minimum values of shear strength for various thicknesses and alloys are given in Table 5. Welds made using the machine settings listed in Table 4 and with a diameter of weld equal to twice the thickness of the sheet plus $^1/_{16}$ in. will exceed the minimum strengths listed in this table. Welds made on energy storage equipment of both the magnetic and condenser types have shear strengths equal to those obtained with alternating current equipment when the welds are of similar size. In some cases it is possible to get slightly larger welds with the energy storage equipment and thus to obtain some increase in shear strength of the welds. The production of welds of small size and of lower strength than listed in Table 5 is to be avoided since settings which give small diameter welds in aluminum are apt under production conditions to produce no weld at all.

Table 5—Minimum Shear Strength of Spot Welds in Lb./Spot for Aluminum Alloys

Thickness of One Sheet of Two Equal Thicknesses Welded, In.	Alloy Welded						
	2S-$^1/_2$H 2S-H	3S-O	3S-$^1/_2$H 3S-H	52S-O	52S-$^1/_2$H 52S-H	53S-W 53S-T 61S-W 61S-T	Alclad 24S-T
0.016	40	40	55	90	90	90	120
0.020	55	55	75	120	120	120	160
0.025	70	70	100	170	170	170	215
0.032	110	110	140	240	240	240	300
0.040	150	140	190	340	340	340	430
0.051	205	180	280	500	510	510	620
0.064	280	250	390	700	720	720	840
0.081	420	340	570	940	1000	1000	1080
0.102	520	480	800	1210	1320	1320	1320
0.125	590	710	1000	1450	1620	1620	1450

Values given in this table are about 65% of average strength obtained when weld diameter is $2T + {}^1/_{16}$ in.

While spot welds are not usually designed to carry tension loading such loading often exists in the form of secondary stress. The tensile strength of spot welds will vary from 20 to 90% of the shear strength and where it is important that such strengths be known, special tests should be made.

Resistance to Corrosion

Spot welds in aluminum alloys 2S, 3S, 52S, 53S and 61S are not selectively attacked by corrosion and spot-welded structures of these materials can be expected to give the same service as the unwelded material. Spot welds

in alclad 24S-T and alclad 17S-T are protected from corrosion by the Alclad coatings on the sheet, even if the weld extends through the coating. Best resistance to corrosion is obtained when the weld does not extend through the coating. Spot welds in 17S-T aluminum and 24S-T aluminum may be selectively attacked under severe corrosion conditions. For this reason spot-welded 17S and 24S construction is to be avoided where corrosion is a factor. If the joint can be protected by paint, particularly in the faying surfaces, some protection of the spot welds is obtained. When 17S or 24S is spot welded to alclad 17S or alclad 24S, the coating on the Alclad material will protect the uncoated material to some extent. However, in time the Alclad coating will be used up and corrosion of the spot weld will ensue.

Seam Welding

Seam-welding equipment for welding aluminum is similar to the a.c. spot-welding equipment except that the electrodes are replaced by roller electrodes from $^3/_8$ to $^5/_8$-in. thick and from 6 to 9 in. in diameter. One or both of these wheels are dressed to 158 to 166° included angle "V" or a 1 to 2-in. radius to concentrate the current in the weld. The wheels and the work are cooled by a generous flow of water directed against the periphery of the wheel near the weld. Usually one of the wheels is driven at an adjustable speed from one to five feet per minute. It is essential for seam welding that the welding timer initiate and cut off the current in synchronism with the supply voltage. Electronically controlled timing equipment is the only satisfactory means available for doing this with sufficient accuracy to produce uniform welds in aluminum. Pressure-tight welds are made by producing a series of overlapping spot welds. The current is cut on and off by the electronic timer, one weld being made for each "on" application of current. The speed of the rolls, together with the "on" plus "off" time, is adjusted so as to get the number of spots per inch shown in Table 6. A number of combinations of cycles "on" and cycles "off" may be used, although the ratio of "on" time to "off" time should be from one-fifth to one-third.

Welding pressure and welding current are adjusted to produce the desired width of weld, which should be about twice the thickness of the material welded plus $^1/_{16}$ in., and the desired surface condition. Poor surface condition may be improved by either increasing the welding pressure or decreasing the welding current. Excessive welding speed will result in sticking of the work to the welding wheel and can be corrected by increasing the "on" plus "off" time, and decreasing the roll speed to give the desired spots per inch. Where a continuous pressure-tight weld is not required, the seam-welding machine may be used to place spot welds at any uniform spacing from about $^3/_8$ to 2 in. In this case the welding "on" plus "off" time is set at from 20 to 60 cycles with the "on" time about one-half of the value recommended in Table 4 for spot welding. The roller speed is adjusted to give the desired spot spacing. Welds so produced are equivalent to spot welds of the same area, although they lack some of the soundness obtained in spot welds. In this case the speed of welding will be from 60 to 180 spots per minute.

As in spot welding, aluminum sticks to the electrodes, so in seam welding

Table 6—Machine Settings for Producing Continuous (Gas-Tight) Seam Welds in Aluminum Alloys

Thickness of One Sheet, In.	Spots Per In.	"On" Plus "Off" Time*, Cycle	Wheel Speed† Ft./Min.	"On" Time‡ Cycles Min.	"On" Time‡ Cycles Max.	Welding Pressure,§ Lb.	Welding Current,§ Amp.	Width of Weld, In.
0.010	25	3½	3.4	½	1	420	19,500	0.08
0.016	21	3½	4.1	½	1	500	22,000	0.09
0.020	20	4½	3.3	½	1½	540	24,000	0.10
0.025	18	5½	3.0	1	1½	600	26,000	0.11
0.032	16	5½	3.4	1	1½	690	29,000	0.13
0.040	14	7½	2.9	1½	2½	760	32,000	0.14
0.051	12	9½	2.6	1½	3	860	36,000	0.16
0.064	10	11½	2.6	2	3½	960	38,500	0.19
0.081	9	15½	2.1	3	5	1090	41,000	0.22
0.102	8	20½	1.8	4	6½	1230	43,000	0.26
0.128	7	28½	1.5	5½	9½	1350	45,000	0.32

* Use next higher full cycle setting if timer is not equipped to give antipole starting of current.

† Wheel speed is adjusted to give desired spots per inch.

‡ "On" time must be set at full cycle setting if "On" plus "Off" time is set at full cycle setting.

§ Welding pressure and welding current are adjusted to give desired width of weld. Values are for 52S-½H aluminum alloy. Use lower pressures for 52S-O or 3S-½H aluminum alloys.

it adheres to the rollers and must be removed by dressing the wheel with a suitable grade of fine abrasive cloth. A fairly coarse grade of cloth is used so as to produce a rough surface on the wheel which prevents slipping between the wheel and the work. On continuous seam welding the wheels must be cleaned after from three to five revolutions, and on intermittent welding after from 10 to 20 revolutions of the wheel. Continuous dressing of the weld may be performed using a medium fine grade of commutator stone held against the wheel with 5 to 10 lb. of pressure. Typical settings for seam welding aluminum alloy 52S-½H are given in Table 6. This table may also be used as a basis for seam welding other alloys, appropriate changes being made in the pressure and the current to produce the desired width of weld.

Flash Welding

Aluminum alloys 2S, 3S, 53S and 61S may be joined by the flash butt welding process. In this process the parts to be welded are held in suitable dies of the flash-welding machine. The parts are driven together with an accelerated motion at the same time voltage from the secondary of the welding transformer is maintained on the parts. As the parts approach each other a violent flashing results which lasts from one-half to one and one-half seconds. The flashing period is terminated by a rapid increase in the speed of the moving part which brings the parts together to put out the flash. The flashing period is terminated by the nearly simultaneous cutting off of the power and a sudden increase in the velocity of the moving die. The ends of the parts being welded are forced together and rapid freezing of the weld takes place because of conduction of heat into the dies.

The process is particularly adapted to making butt or miter welds between aluminum sections of less than one square inch cross-section area. For mechanical reasons the process is limited to sections greater than 0.050 in. thick. The process has also been adapted to joining aluminum and copper bars and tubing, and the joints so produced fail in the aluminum outside of the weld. If annealed aluminum is used to make the joints, the joints are not brittle.

A machine for flash welding aluminum should have a maximum secondary current output of approximately 100,000 amp. per sq. in. of material to be welded. Secondary voltages from 2 to 10 v. have been used. The amount of material flashed off varies from $^1/_4$ in. to $^1/_2$ in. and the upset motion varies from $^1/_{16}$ to $^3/_{16}$ in. depending upon the section welded. In general, the upset motion is about equal to the thickness of the section welded. The flashing time varies from 30 cycles for welds in small sections, such as $^1/_4$ to $^5/_{16}$ in. o.d. aluminum tubing, to 70 cycles for a $^1/_4$ x 2 in. solid bar. The welding current is cut off after the parts have come into contact. This hot upsetting period should be from two to five cycles in duration.

VIII. CHARACTERISTICS OF WELDS IN THE ALUMINUM ALLOYS

The proper application of welding to aluminum and aluminum alloy structures involves an understanding of the metallurgical characteristics of these materials, in addition to the use of correct welding technique. The effect of heat from the various welding methods on the strength and resistance to corrosion of the alloys is described as follows.

The most widely used grade of metal for welded parts is commercially pure aluminum. This grade is produced as sheet, tubing, extruded shapes and other commercial forms. The strength of commercially pure aluminum is dependent on the amount of cold work the metal receives during fabrication, the metal being marketed in the soft, intermediate or full-hard temper. When the material is arc or gas welded, however, the welding heat removes the cold work in an area about two to four times the thickness of the section at the weld. The tensile strength across a butt weld is not greater than the annealed strength of the material regardless of the temper welded. Welds in this material are characterized by excellent ductility and a resistance to corrosion approximately the same as that of the parent material.

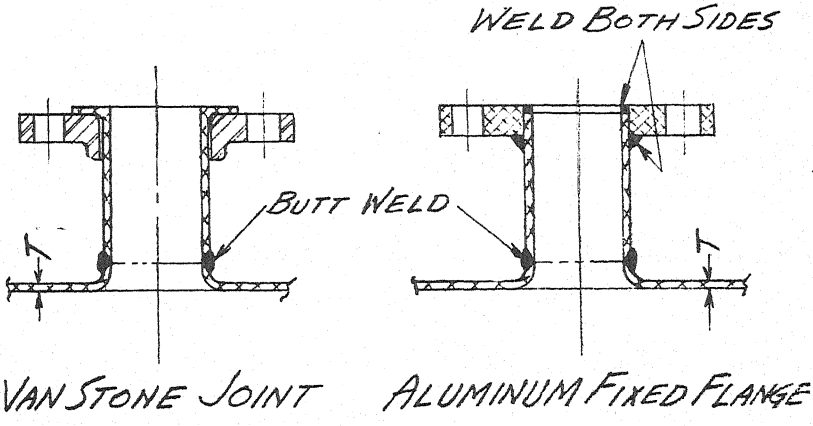
The above remarks apply as well to welds in material of higher purity than commercially pure aluminum. Aluminum of 99.1 to 99.7% purity is sometimes required to obtain better resistance to attack from certain chemicals, such as hydrogen peroxide, or to prevent contamination of the products handled, such as beer or varnish products. In these applications a filler rod at least as high in purity as the parent metal should be used to obtain comparable resistance to corrosion in the weld and the parent metal.

By alloying aluminum with $1^1/_4$% manganese, a material is produced with higher tensile and yield strength, in which the weldability is substantially the same as pure aluminum and the welds have excellent ductility and resistance to corrosion. This alloy is one in which the tempers are produced by cold working. Hence, a strength not greater than that of the soft or annealed temper is obtained in the weld.

Table 7—Typical Mechanical Properties of Wrought Aluminum Alloys

Alloy	Temper	Yield Strength, Psi.	Ultimate Strength, Psi.	Elongation,* % in 2 In.	Brinell Hardness†
Aluminum	Soft	5,000	13,000	35	23
	1/2 Hard	14,000	17,000	9	32
	Hard	21,000	24,000	5	44
Al-1.25% Mn	Soft	6,000	16,000	30	28
	1/2 Hard	18,000	21,000	8	40
	Hard	25,000	29,000	4	55
Al-2.5% Mg-0.25% Cr	Soft	14,000	29,000	25	45
	1/2 Hard	29,000	37,000	10	67
	Hard	36,000	41,000	7	85
Al-0.7% Si-1.25% Mg	Soft	7,000	16,000	25	26
	W	20,000	33,000	22	65
	T	33,000	39,000	14	80
Al-0.6% Si-1.0 Mg-0.25% Cr	Soft	8,000	18,000	22	30
	W	21,000	35,000	22	65
	T	39,000	45,000	12	95

* Sheet specimen 1/16 in. thick.
† 500 kg.—10 mm. ball.
W—Solution heat treatment.
T—Solution heat treatment plus artificial aging.



For tanks with sidewalls 3/16" thick or over, the minimum I.P.S. tube for which the tank can be flanged for butt welding to fitting is shown in the table below:

MINIMUM I. P. S.	1"	2"	4"	6"
T	3/16"	1/4"	3/8"	1/2"

Fig. 2—Tubular Connections

Table 8—Data for Gas Welding Tank Structures

Gage, In	Gas Used	Diam. Opening Tip, In.	Wire Diam., In.	Wire per 100 Ft., Lb.	Flux per 100 Ft., Lb.	Rate of Welding, Ft./Hr.
1/16	Oxy-hydrogen	0.055	0.125	6.0	2.0	12.0
1/8	Oxy-hydrogen	0.075	0.146	12.5	3.0	10.0
1/4	Oxyacetylene	0.075	0.184	20.0	5.5	8.0
3/8	Oxyacetylene	0.084	0.184	30.0	10.0	6.0
1/2	Oxyacetylene	0.095	0.250	35.0	15.0	3.5
5/8	Oxyacetylene	0.095	0.312	40.0	18.0	3.5

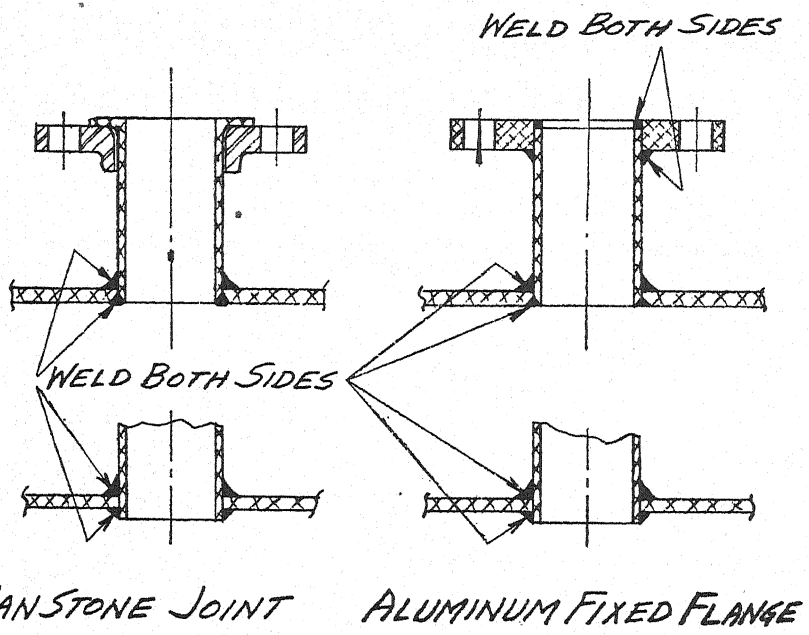


Fig. 3—Tubular Connections with Sidewalls Too Heavy for Flanging

An alloy of aluminum with 2.5% magnesium and 0.25% chromium has substantially higher mechanical properties, and resistance to corrosion as good as commercially pure aluminum, and is finding a considerable number of applications where welding is required. In this case, some trouble may be apparent in welding gages heavier than 1/4 in. with gas welding because of the tendency for the parent metal to show cracks near the weld when the joint cools. No such difficulty is experienced when this alloy is resistance or metallic arc welded.

By alloying aluminum with certain other metals a class of materials has been developed in which the mechanical properties are increased by heat treatment. Two of these alloys, an aluminum-magnesium-silicon-chromium alloy and an aluminum-silicon-magnesium alloy, are used extensively in welded construction. In this case the welding heat partially obliterates

the heat-treated structure and the strength of the welds is intermediate between the annealed and heat-treated strength of the alloy. The number, length and type of the welds determine the extent of the annealing effect, and strength of a welded structure of these materials is not accurately predictable. In most cases it is desirable to test the completed part to determine the strength.

Typical mechanical properties of these materials are shown in Table 7.

Shop Practices

The rate of welding aluminum alloys in the shop is comparable to, or slightly faster than that obtained on other materials. Individual jobs may vary considerably, depending on the design. However, the rate of welding and the flux and rod consumption for gas welding of tank structures are approximately as shown in Table 8. This information necessarily represents average conditions and is suitable for estimating purposes.

In attaching manhole connections and fittings to tanks it is desirable to flange out the sidewalls and butt weld to the fittings. In view of the ease of forming and the ductility of aluminum, this is generally not difficult. Typical practices for attaching fittings are shown in Figs. 2 and 3.

CHAPTER 24

NICKEL AND HIGH-NICKEL ALLOYS*

Monel, Nickel, Inconel, High-Nickel-Chromium-Iron Heat-Resisting Alloys, Hastelloy Alloys, Illium

I—INTRODUCTORY

THIS chapter contains detailed information on the joining and properties of commercial forms of rolled nickel, and those of its alloys that contain more than 50% nickel. The following materials are discussed, with trade names used where applicable:

I. Nickel
   (*a*) Rolled nickel
   (*b*) "Z" nickel
II. Nickel-copper alloys
   (*a*) Monel
   (*b*) "K" Monel
   (*c*) "H" Monel
   (*d*) "S" Monel
III. Nickel-chromium and other high-nickel alloys
   (*a*) Inconel
   (*b*) Heat-resisting alloys
   (*c*) Illium
   (*d*) Hastelloy alloys

A brief description of these materials follows, while their nominal chemical compositions, physical constants and mechanical properties are given in Tables 1, 2 and 3.

Rolled Nickel is commercially pure, malleable nickel, magnetic, with a nominal "nickel" content of 99.4%. It has high resistance to corrosion.

"Z" Nickel is an age-hardening, high-nickel alloy in which great strength and hardness are accompanied by the high resistance to corrosion that is characteristic of nickel. It is magnetic. Since it is used largely for corrosion-resistant springs, diaphragms or similar flexing parts, welding is employed only incidentally on this material.

Monel, a rolled material, containing approximately 67% nickel and 30%

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copper, has high strength, hardness and toughness and good resistance to corrosion. It is slightly magnetic.

"K" Monel is a non-magnetic, age-hardening alloy, containing approximately 3% aluminum. Its strength and hardness, particularly in large sections, are comparable with those of heat-treated alloy steels, and its resistance to corrosion is similar to that of Monel.

"H" Monel contains 2.75 to 3.25% silicon but otherwise has the composition of cast Monel. The silicon provides increased, but not maximum, hardness with good ductility. This cast alloy has the same order of resistance to corrosion as cast Monel. Information on the welding properties of "H" and "S" Monel is given on page 934.

"S" Monel contains approximately 4% silicon which confers age-hardening characteristics. The hardness of this cast alloy is of the order of 320 Brinell as-cast and may be increased to 375 by suitable thermal treatment. The alloy has the same order of resistance to corrosion as Monel and "H" Monel. Information on the welding of "S" and "H" Monel is given on page 934.

Inconel is a rolled, high-strength, non-magnetic, nickel-chromium-iron alloy containing approximately 80% nickel and 13% chromium. Because of freedom from scaling and intercrystalline attack it has been applied extensively for service at elevated temperatures.

The *Hastelloy* alloys consist of four types of nickel-base alloys, designated as A, B, C and D. Developed primarily for resistance to the highly corrosive mineral acids, they also possess excellent mechanical properties. These properties together with the nominal compositions are given in Tables 1, 2 and 3. The welding characteristics of Hastelloy alloys are given beginning on page 941.

Hastelloy Alloy A is a nickel-molybdenum-iron alloy, as strong as alloy steels, particularly resistant to hydrochloric and sulphuric acids. It is made in the following forms: castings, wrought parts, rolled sheet, wire and welded tubing.

Hastelloy Alloy B is a nickel-molybdenum-iron alloy with somewhat higher molybdenum content than alloy A. It is used for equipment handling boiling hydrochloric acid, wet hydrochloric acid gas and sulphuric acid. It is made in the same forms as alloy A.

Hastelloy Alloy C is a nickel-molybdenum-chromium-iron alloy capable of withstanding strong oxidizing agents. It is available as castings and hot-rolled sheet and plate.

Hastelloy Alloy D, available in cast form only, is an alloy of nickel and silicon plus small amounts of other metallic elements. It is exceptionally resistant to sulphuric acid in all concentrations up to the boiling point.

Illium is an alloy composed largely of nickel and chromium, with small amounts of copper, molybdenum, manganese and tungsten, resistant to a variety of corrosives. Illium G is the cast form, whereas Illium R, having the same general composition, is produced in wrought form as rolled strip, sheets, plates, clad steel, welded tubing and wire. Its nominal composition and mechanical properties are to be found in Tables 1, 2 and 3. Information on the welding of Illium is given on page 943.

Nickel-chromium-iron heat-resisting alloys are chemically and mechani-

Table 1—Nominal Chemical Composition

Material	Nickel, %	Copper, %	Iron, %	Manganese, %	Silicon, %	Carbon, %	Sulphur, %	Aluminum, %	Chromium, %	Molybdenum, %	Tungsten, %
I. Nickel:											
(*a*) Rolled nickel	99.4	0.1	0.15	0.2	0.05	0.1	0.005	..	...	..	..
(*b*) "Z" nickel	98	..	...	...	...	..	...	..	...	..	..
II. Nickel-copper Alloys:											
(*a*) Monel	67	30	1.4	1	0.1	0.15	0.01	..	...	..	..
(*b*) "K" Monel	66	29	0.9	0.4	0.50	0.15	0.005	2.75	...	..	..
(*c*) "H" Monel	65	29.5	1.5	0.9	3	0.1	0.015	..	...	..	..
(*d*) "S" Monel	63	30	2	0.9	4	0.1	0.015	..	...	..	..
III. Nickel-Chromium and Other High-Nickel Alloys:											
(*a*) Inconel	79.5	0.2	6.5	0.25	0.25	0.08	0.015	..	13	..	..
(*b*) Heat-resisting alloys											
HX	65–68	..	...	...	...	..	...	..	15–19	..	..
HW	59–62	..	...	...	...	..	...	..	10–14	..	..
(*c*) Illium G and R	54–58	5–7	5–7	0.75–1.5	0.65 max.	0.2 max.	...	..	22–24	5–7	2
(*d*) Hastelloy											
Alloy A	58	..	20	2	...	..	...	..	...	20	..
Alloy B	62	..	4	...	...	..	...	..	...	29	..
Alloy C	58	..	6	...	...	..	...	..	14	17	5
Alloy D	85	3	...	...	10	..	...	2	...	..	..

Table 2—Physical Properties

Material	Melting Range, °F.	Thermal Conductivity, Btu./Sq. Ft./In./Hr./°F.	Coefficient of Thermal Expansion, 10^6, In./In./°F.	Electrical Resistivity 32°F., Ohms/Cir. Mil. Ft.
Nickel	2615–2635	420	7.2[d]	37
"Z" nickel	2615–2635	420	7.2[d]	100
Monel	2370–2460	180	7.8[d]	290
"K" Monel	2400–2460	130	7.8[d]	350
"H" Monel	2350–2400	180	...	370
"S" Monel	2300–2350	180	8.7[f]	380
Inconel	2540–2600	104	6.4[d]	...
Heat-resisting alloys HX*, HW*, HW*	2300–2500	94†	7.6[d]†	675†
Illium G	2375	...	7.5[d]	735
Hastelloy alloys				
Alloy A	2370–2425	116	8.6[e]	760
Alloy B	2410–2460	78.5	8.1[e]	813
Alloy C	2320–2380	87	8.5[e]	800
Alloy D	2030–2050	145	10.1[e]	680

[d] 32–212°F. [e] 32–1800°F. [f] 70–1000°F.
* Alloy Casting Institute designation—refer to page 940.
† Approximate.

Table 3—Mechanical Properties

Material Form	Yield Strength, 1000 Psi.	Tensile Strength, 1000 Psi.	Elongation in 2 In., %	Hardness Rockwell "B"	Hardness Brinell 3000 Kg.	Modulus of Elasticity, 10^{-6} Psi.
Monel						
Plate—Hot Rolled:						
Annealed	25–45	70–85	50–30	60–75	110–140	26
As-rolled	40–90	80–110	45–20	75–98	...	26
Sheet—Standard Cold Rolled	25–45	65–85	50–20	61–73	...	26
Tube—Cold Drawn:						
Annealed	25–35	65–85	50–20	55–70	...	26
As-drawn	60–120	90–125	20–10	90–105	...	26
"K" Monel						
Strip—Cold Rolled:						
Soft	50–65	90–105	45–30	75–85	...	26
Soft, Heat Treated	90–110	130–150	25–10	20–30[a]	...	26
1/2 Hard	85–105	125–145	20–10	15–28[a]	...	26
1/2 Hard H.T.	110–130	150–180	15–5	28–35[a]	...	26
Full Hard	105–120	145–165	8–2	25–32[a]	...	26
Full Hard H.T.	125–145	170–200	10–2	33–40[a]	...	26
Rods—Cold Drawn:						
Annealed	40–60	90–110	45–35	75–90	140–180	26
Annealed H.T.	90–110	130–150	30–20	21–25	240–260	26

(*Continued an next page*)

Material Form	Yield Strength, 1000 Psi.	Tensile Strength, 1000 Psi.	Elongation in 2 In., %	Hardness Rockwell "B"	Hardness Brinell 3000 Kg.	Modulus of Elasticity, 10^{-6} Psi.
Nickel						
Plate—Hot Rolled:						
Annealed	15–30	60–80	50–35	40–65	90–120	30
As-rolled	20–75	70–100	45–30	50–100	100–200	30
Sheet—Standard						
Cold Rolled	15–30	60–80	50–35	40–65	...	30
Tube—Cold Drawn:						
Annealed	15–30	60–80	50–35	40–65	...	30
As-drawn	50–80	80–95	25–15	80–100	...	30
Inconel						
Sheet—Cold Rolled:						
Soft	30–45	80–100	50–35	65–85	...	31
Tube—Cold Drawn:						
Annealed	30–50	80–110	50–35	65–85	...	31
As-drawn	65–140	110–160	20–2	8–35[a]	...	31
Heat Resisting Alloy HW—60 Ni, 15Cr						
Hot Rolled	60	110	35	...	200	...
Heat Resisting Alloy—80 Ni, 20 Cr						
Cold Drawn:						
Annealed	60	110	35	...	...	...
Hastelloy Alloy A						
Cast	42–45	69–77	8–12	85–94	155–200	27
Rolled						
(Annealed)	47–52	110–120	40–48	94–97	200–215	27
Hastelloy Alloy B						
Cast	55–57	75–82	6–9	92–99	190–230	30.75
Rolled						
(Annealed)	60–65	130–140	40–45	96–100	210–235	30.75
Hastelloy Alloy C						
Cast	45–48	72–80	10–15	89–97	175–215	28.5
Rolled						
(Annealed)	55–75	115–128	25–50	84–95	160–210	28.5
Hastelloy Alloy D						
Cast	...	36–40	0	50–55	...	28.85
Illium						
	Elastic Limit					
"G"—Cast	50–63	60–73	...	...	160–210	...
"R"—Rolled						
(Annealed)	45–55	95–105	30–45	...	175–240	...

[a] Rockwell C.

cally stable at elevated temperatures with excellent resistance to oxidizing, reducing and other high-temperature corrosive atmospheres. These materials are made in cast, sheet and wrought bar form. These materials are used particularly in oil refinery stills, steel mill and heat-treating furnace parts, carburizing boxes, chemical processing equipment, in the glass industry and for other high-temperature applications. The details of welding these materials are given in the section beginning on page 940.

II—JOINING MONEL, NICKEL AND INCONEL

The joining processes that are used for steel are applicable, though sometimes with slight modification, to Monel, "K" Monel, nickel, "Z" nickel and Inconel. They are tabulated below and discussed at length in succeeding subsections. Additional information is contained in technical publications of the manufacturer.

Widely Used Processes	Less Widely Used Processes
Welding	Welding
Electric-arc	Atomic-hydrogen
Oxyacetylene (gas)	Carbon arc
Resistance	Submerged melt
Silver brazing (silver soldering)	Furnace brazing
Soft soldering	Brass brazing

Only the first five processes can be considered as having broad application to the high-nickel materials. Since all five produce very satisfactory joints, the choice among them is determined by:

(1) The corrosive environment to which equipment will be exposed (to establish whether welding, silver brazing or soft soldering is applicable),
(2) the thickness of material being joined,
(3) the design of the piece of equipment and
(4) the design of the individual joints in the equipment.

The oxy-hydrogen flame is not practicable for the welding of nickel or nickel alloys because of its low temperature. Hammer welding is not possible because fusion does not occur unless the metal is melted.

Good properties are inherent in welded joints in all five materials, and no after-treatment, either thermal or chemical (passivation), is needed nor recommended to retain or restore corrosion resistance. The joints are equivalent in corrosion resistance and strength to the parent metal. Thermal treatments, however, may be applied for special reasons, as, for example, a stress relief of a fabricated Monel structure to meet Code requirements, or an age-hardening treatment to increase strength and hardness in "K" Monel.

Since the coefficients of expansion of the high-nickel materials are practically the same as of steel, warping and buckling resulting from a welding operation will be essentially the same as those obtained for steel in the same construction.

A summary of oxyacetylene and metal-arc welding rods for Monel, nickel and Inconel is given in Table 4.

Mechanical Properties of Fusion Welds

The mechanical properties of the various types of fusion welds are to be found in the sections describing the joining method.

Table 4—Oxyacetylene and Metal-Arc Welding Rods and Fluxes

Welding Wire or Rod	Type of Welding	Application
Monel gas-welding wire	Oxyacetylene	General purpose oxyacetylene welding of Monel. Used with a flux
Monel electrode	Metal-arc	All metal-arc welding of Monel to Monel, of Monel to steel and of nickel to steel
Nickel gas-welding wire	Oxyacetylene	Oxyacetylene welding of pure nickel. No flux is required
Nickel electrode	Metal-arc	Metal-arc welding of pure nickel
Inconel gas-welding wire	Oxyacetylene	Oxyacetylene welding of Inconel. A flux is recommended
Inconel electrode	Metal-arc	Metal-arc welding of Inconel
"K" Monel gas-welding wire	Oxyacetylene	Oxyacetylene welding of "K" Monel. Used with a flux
"K" Monel electrode	Metal-arc	Metal-arc welding of "K" Monel to "K" Monel

Joint Design

The joint designs applicable in fabricating Monel, nickel and Inconel are found within the section describing the welding method. The range of gages for each type of joint is given, together with the design of the welding groove. In general, it will be observed that the joint designs are essentially those used for plain carbon steel welded fabrication.

Surface Preparation for Welding

Electrodes and oxyacetylene welding wires and fluxes for nickel and nickel alloys have been developed for use on clean metal, such as standard cold-rolled sheet, pickled hot-rolled plate or cold-drawn rod. To insure satisfactory welding of hot-rolled plate, hot-rolled bar stock or material that has been hot worked otherwise in processing or fabrication, it is necessary, first, to remove the thin, darkly colored oxide film from the immediate vicinity of the area to be welded, either mechanically by machining, sandblasting, grinding or rubbing with emery cloth, or chemically by pickling. A hot-rolled plate that has been machine beveled in preparation for a butt joint needs no further cleaning, because a clean metallic surface is exposed on the face of the bevel. Difficulty in the form of a wandering arc may be encountered if the oxide is not removed. The sand-cast surfaces of Monel, nickel or Inconel castings must be removed from the areas to be welded by either rough grinding or machining.

Electric-Arc Welding

Satisfactory joints are produced by both oxyacetylene and electric-(metal-) arc welding. The choice, in which sheet steel practice is an acceptable guide, is determined, not by the composition of the material but by the thickness, the design of the piece and the design of the individual joint. Electric welding, if applicable, will produce less buckling than gas welding.

Table 5—Average Tensile Properties of Welded Butt Joints in Monel, "K" Monel, Nickel and Inconel (to Nearest 100 Psi.)

Plate Thickness, In.	Type of Butt Joint	Electrode* Diam., In.	Tensile Strength, Psi.						Minimum Elongation in Free Bend, %	
			Full Section (Long Gage)			Reduced Section (Short Gage)				
			Flat	Vertical	Over-hand	Flat	Vertical	Over-hand		
Monel										
1/8	Square	3/32	75,500	76,500	76,600	78,600	78,800	77,800	30	
3/16	Single vee	1/8	77,300	76,900	76,300	78,100	79,600	79,100	30	
3/8	Single vee	5/32	78,400	80,200	79,800	81,700	83,200	82,400	30	
7/16	Single vee	5/32	77,200	..	..	79,800	..	..	30	
3/4	Double vee	5/32	..	..	..	84,400	..	..	30	
Nickel										
1/8	Square	3/32	69,900	..	..	71,400	..	..	25	
3/16	Single vee	1/8	69,100	..	..	71,200	..	..	25	
3/8	Single vee	5/32	69,400	..	..	74,000	..	..	25	
11/16	Single vee	5/32	..	..	..	77,400	..	..	25	
Inconel										
1/8	Square	3/32	95,700	..	..	106,200	..	..	30	
3/8	Single vee	5/32	92,400	..	..	93,700	..	..	30	
5/8	U Groove	1/8 and 5/32	..	..	..	81,500	..	..	28†	
"K" Monel										
				As welded			Age-hardened		As welded†	Age-hardened†
1/8	Square	5/32	89,100	..	..	129,900	..	..	46	19
1/4	Single vee	5/32	90,900	..	..	128,700	..	..	51	18
3/8	Single vee	5/32	95,500	..	..	121,400	..	..	40	14

* Welding electrodes were used as follows: Monel—No. 130X Monel electrode. "K" Monel—No. 134 "K" Monel electrode. Nickel—131 nickel electrode. Inconel—No. 132 Inconel electrode.

† Actual values.

In electric-arc welding, practices in joint design, layout and welding manipulation similar to those used in making quality welds in steel are followed.

Nickel and Monel can be welded in all positions with the same facility as steel. While Inconel can be welded in any position, it is best, when possible, to position the work for down-hand or flat welding.

In general, the lower limit of thickness of sheet for electric-arc welding is set at 0.037 in., but with the recently introduced rectifier-type welding equipment, thicknesses as light as 0.018 in. have been welded with electrodes smaller than $^1/_{16}$ in. diameter.

The procedures for "K" Monel and "Z" nickel are described separately on pages 931 and 932.

Mechanical Properties of Welds

Tensile properties of electric-arc welded joints in Monel, "K" Monel, nickel and Inconel are listed in Table 5. All welds were machined flush with the plate before testing.

Electrodes

The types of electrodes available, all shielded-arc, and the recommended applications for each, are listed in Table 4. A guide to the selection of proper electrode size is given in Table 6. Electrodes should be left in their sealed bundles until they are to be used, and kept in a dry place.

Table 6—Electrode Diameter vs. Sheet Thickness

Electrode Diam., In.	Approximate Number of Electrodes per Lb.	Sheet Thickness on Which Electrode Is Used, In.
$^5/_{64}$	51	Up to and including 0.062
$^3/_{32}$	36	0.062, 0.078, 0.093
$^1/_8$	16	0.109, 0.125, 0.140, 0.156
$^5/_{32}$	10+	0.140 and thicker
$^3/_{16}$	7	0.375 and thicker, and for overlaying
$^1/_4$	4+	Used for overlaying

The electrodes are for use with d.c. motor-generator or rectifier-type welders and will produce satisfactory joints when so used. They will not produce satisfactory welds with a.c. transformer-type welders. Diameters of $^3/_{16}$ in. and smaller are the most widely used for welding. The $^3/_{16}$-in. and $^1/_4$-in. diam. electrodes are recommended for overlaying.

Table 7—Recommended Current Ranges for Metal-Arc Welding Electrodes

Electrode Diameter, In.	Current Range, Amp.			
	Monel	Nickel	Inconel	"K" Monel
$^5/_{64}$	25– 40	35– 55	30– 45	..
$^3/_{32}$	45– 60	65– 85	45– 60	45– 60
$^1/_8$	60– 95	80–110	60– 95	60– 95
$^5/_{32}$	80–150	120–170	100–135	80–150
$^3/_{16}$	140–190	160–210	110–195	..
$^1/_4$	170–260	...	...	..

Polarity.—The high-nickel electrodes are used on reversed polarity only, i.e., electrode positive, work negative.

Currents.—Each diameter electrode has an optimum amperage range in which it has good arcing characteristics and outside of which the arc becomes unstable. The limits of satisfactory operation are given in Table 7.

Joint Design

A summary of electric-arc welding data for Monel, nickel and Inconel is given in Table 8.

Corner welds and lap joints may be used where high stresses are not encountered. In such equipment as pressure vessels, butt joints are preferred for electric welding since stresses act axially rather than eccentrically as in lap joints.

Beveling is not recommended for sheets of 0.140 in. or less in thickness; for 0.156-in. and thicker material, edges should be beveled to $37^1/_2°$ (75° total included angle) for vee joints, and to 15° for U and J grooves. In all cases, it is desirable to retain a lip of $^1/_{16}$ in., or slightly more, at the base of the bevel.

To obtain uniform and accurate fits, beveling is done best by machine, usually on a plate planer or other machine tool. Neither oxyacetylene nor carbon-arc cutting is recommended, as the cuts made are poor and the area adjacent to the cut is oxidized badly.

Jigs and Clamps

Proper jigging facilitates any welding operation greatly, particularly by minimizing buckling. This is true not only for non-ferrous alloys of high melting point but for steels as well. Reference should be made to Chapter 32C for a discussion of principles of jigging for welding.

Jigs for electric-arc welding are designed with a groove to permit penetration of weld metal. Grooves should be extremely shallow, usually $^1/_{64}$ to $^1/_{32}$ in. maximum depth, and $^3/_{16}$ to $^1/_4$ in. wide.

Preheating

In general, preheating is neither required nor recommended for arc welding wrought nickel and its alloys, but if the metal temperature should drop to 32°F. or lower, the joint should be preheated to 70°F. or over for 6 in. on each side of the welding groove.

Simple castings of Monel, nickel or Inconel which are to be electric-arc welded to equipment, need not be preheated, but preheating to 200 to 300°F. is desirable for complicated castings.

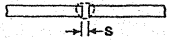
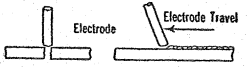
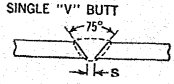
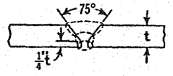
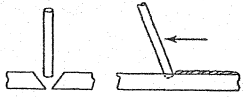
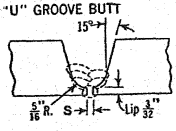
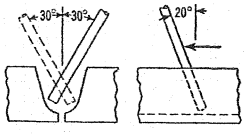
Electrode Position and Manipulation

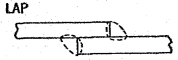
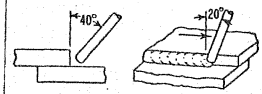
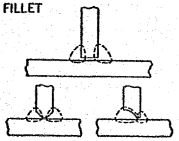
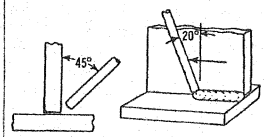
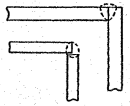
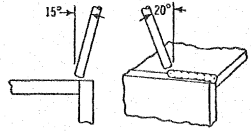
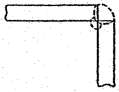
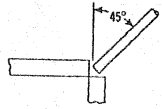
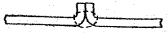
The best electrode position for down-hand welding is at an incline of about 20° from the vertical and ahead of the puddle, as in Table 8, column 10. This position is best suited for control of the molten flux and elimination of slag trapping. It is essential that a short arc be maintained.

For overhead welding, the only change necessary is a slightly further shortening of the arc and lowering of the current strength by 5 to 15 amp.

In vertical welding also, the current must be lowered slightly from the

Table 8—Electric-Arc Welding Data for Monel, Nickel and Inconel

Joint Type 100% Penetration Is Assumed	Minimum and Maximum Thickness (U.S.S. Gage) for Various Positions, In.		Root Spacing "S" Between Plates in Column 1, In.		Joint Backing (Copper Bars Are Preferred)	Tack Welds	Electrode Diam., In.		No. of Passes Required to Complete the Joint	Electrode Positions for Down-Hand Welding, End and Side Views
	Min.	Max.	For Min. Gage	For Max. Gage			For Min. Thickness	For Max. Thickness		
Column 1	2	3	4		5	6	7	8	9	10
SQUARE BUTT 	(*f*) 0.037 (20 ga.)	0.140 (10 ga.)	0	1/16	Backing is necessary for thicknesses 0.050 in. (18 ga. U.S.S.) and thinner	1/8 in. long on 3–4 in. centers	5/64	1/8	1	
	(*v*) 0.062 (16 ga.)	0.140 (10 ga.)	0	1/16			5/64	1/8	1	
	(*o*) 0.050 (18 ga.)	0.140 (10 ga.)	0	3/32			3/32	1/8	1	
SINGLE "V" BUTT  OR SINGLE "V" (WITH LIP) BUTT 	(*f*) 5/32 (9 ga.)	5/16	1/16	3/32		1/4–1/2 in. long on 6-in. centers	1/8	5/32	1 for 5/32-in. or 3/16-in. plate 2 for 1/4-in. plate 3 for 3/8-in. plate 3 or 4 for 7/16 and 1/2-in. plate	
	(*v*) 5/32 (9 ga.)	3/8	1/16	3/32			1/8	5/32		
	(*o*) 5/32 (9 ga.)	5/16	1/16	3/32			1/8	5/32		
	(*f*) 5/32 (9 ga.)	1/2	1/16	1/8		1/4–1/2 in. long on 6-in. centers	1/8	3/16		
	(*v*) 3/16 (7 ga.)	7/16	1/16	1/8			1/8	3/16		
"U" GROOVE BUTT 	(*f*) 1/2	None	1/16	3/32		1 in. long on 8-in. centers	1/8	5/32 and 3/16	Depends on plate thickness	
	(*v*) 1/2	None	1/16	3/32			1/8	5/32 and 3/16		

LAP 	(*f*) 0.037 (20 ga.) (*v*) 0.062 (16 ga.) (*o*) 0.062 (16 ga.)	None None None	None None None	If design permits, backing should be provided for thicknesses 0.062 in. (16 ga. U.S.S.) to 0.093 in. (13 ga. U.S.S.)	1/4 in. long on 6-in. centers	5/64 5/64 5/64	5/32 or 3/16 5/32 or 3/16 5/32 or 3/16	1 or more	
FILLET 	(*f*) 0.062 (16 ga.) (*v*) 0.062 (16 ga.) (*o*) 0.062 (16 ga.)	None None None	None None None		1/4–1/2 in. long on 6-in. centers	3/32 3/32 3/32	5/32 or 3/16 5/32 or 3/16 5/32 or 3/16	1 or more	
CORNER 	(*f*) 0.050 (18 ga.) (*v*) 0.062 (16 ga.) (*o*) 0.062 (16 ga.)	1/8 (11 ga.) 1/8 (11 ga.) 1/8 (11 ga.)	None None None		1/4 in. long on 4-in. centers	5/64 5/64 5/64	1/8 1/8 1/8	1 1 1	
CORNER 	(*f*) 3/32 (13 ga.) (*v*) 3/32 (13 ga.) (*o*) 3/32 (13 ga.)	None None None	None None None		1/4 in. long on 4–8-in. centers	1/8 1/8 1/8	5/32 or 3/16 5/32 or 3/16 5/32 or 3/16	Depends on plate thickness	
	(*f*) 0.037 (20 ga.)	0.062 (16 ga.)	None		1/8 in. long on 4–8-in. centers	5/64	3/32	1	Same as for square butt (at top of table)
 Grind Only to Sound Metal	(*f*) 0.031 (22 ga.)	0.050 (18 ga.)	None		1/8 in. long on 4–8-in. centers	5/64	3/32	1	Same as for square butt (at top of table)

(*f*) = Flat Position. (*v*) = Vertical Position. (*o*) = Overhead Position.

normal flat welding heat. For metal 0.062 in. and 0.078 in. thick, welding should be started at the top and progressed straight downward. On metal thicker than 0.078 in., welding can be carried on from either the bottom upward or the top downward. The electrode should be held approximately at right angles to the plate being welded.

A straight drag, or string bead laid down without weaving is used for single-bead work, or in close quarters on thicker sections, as in the bottom of a deep groove. Weaving, if necessary or desirable, can be used. Since the weld metal does not spread as in welding steel, but must be placed where required, it is necessary to weave the electrode slightly for vertical and overhead welding. Bead widths range from $^1/_8$ to $^5/_{16}$ in. Wider, and usually flatter, beads are obtained by weaving and range from $^3/_8$ in. to a maximum of $^3/_4$ in. In general, wider beads should not be used even for overlaying as this requires excessive puddling of the pool of molten metal.

A 24- to 27-volt arc, usually referred to as a "short" arc, should be maintained during welding. Arc blow is not encountered and there will be no spatter with the high-nickel materials, unless excessive amperages or too long an arc is being used.

Heat Effect of Welding

There is no detrimental effect on the parent metal from the heat of arc welding. The only possible effect is a very slight grain enlargement in a very narrow band at the edge of the weld, referred to as the heat-affected zone. Strength and ductility of the parent metal are not altered noticeably.

Figures 1 to 3 show typical microstructures of electric-arc welds made in Monel, nickel and Inconel.

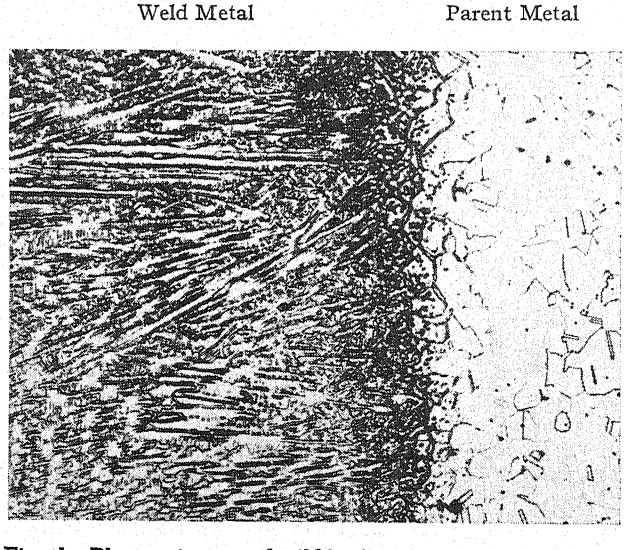


Fig. 1—Photomicrograph (100 ×) of Monel Electric-Arc Weld Showing Parent Metal in Right Third, Weld Metal in Left Two-Thirds and Fusion Zone Between Parent and Weld Metal

Weld Metal Parent Metal

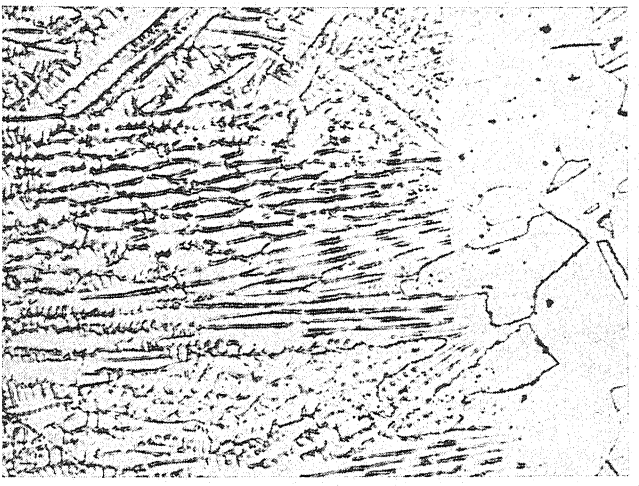


Fig. 2—Photomicrograph (100 ×) of Nickel Electric-Arc Weld Showing Parent Metal in Right Third, Weld Metal in Left Two-Thirds and Fusion Zone Between Parent and Weld Metal

Weld Metal Parent Metal

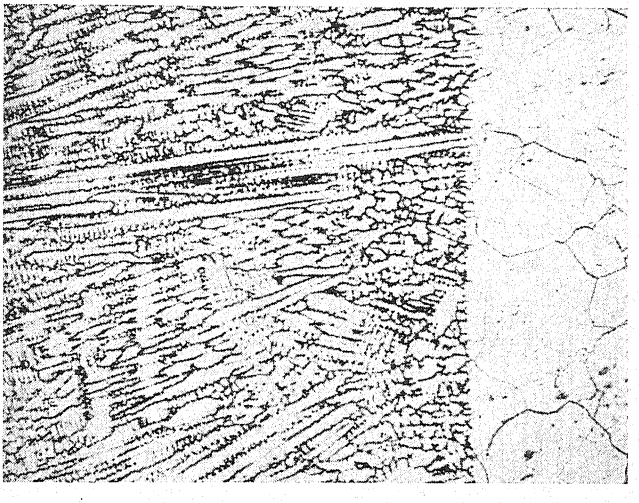


Fig. 3—Photomicrograph (100 ×) of Inconel Electric-Arc Weld Showing Parent Metal in Right Third, Weld Metal in Left Two-Thirds and Fusion Zone Between Parent and Weld Metal

Cleaning and Finishing Welds

The flux is removed easily from welds with hand tools, or with a hand or powered wire brush. When making multiple-pass welds, it is very important that all flux or slag be removed before laying down each succeeding bead. The flux must be removed if the fabricated part is to be stress-relieved or if, in the case of a "K" Monel part, it is to be age-hardened.

Welds may be left either in the as-welded or ground and polished condition.

Oxyacetylene Welding

Oxyacetylene welding is being applied to the fabrication of all types of equipment in the many fields in which the high-nickel materials are used. Good welding is accomplished with it in flat, vertical or overhead positions. As has been stated previously, its selection over arc welding is determined by factors of design and thickness of material.

Mechanical Properties of Welds

Tensile properties of oxyacetylene welded joints in Monel, nickel and Inconel are listed in Table 9.

Table 9—Tensile Properties of Oxyacetylene Welded Joints

Material	Tensile Strength, Min. Psi.
Nickel	60,000
Monel	65,000
Inconel	75,000

Welding Wire

The available welding wires, listed in Table 4, are of practically the same composition as the alloy being welded. This is necessary to insure uniform corrosion resistance without galvanic effects. Wires are furnished in the sizes listed in Table 10.

Table 10—Gas-Welding Wire Diameter vs. Sheet Thickness

Diam. of Wire, In.	Sheet Thickness on Which Welding Wire Is Used, In.	Welded Seam per Lb., of Welding Wire, Ft.
1/16	0.031 to 0.062	85
3/32	0.062 to 0.109	42
1/8	0.109 to 0.140	21
5/32	0.140 to 0.187	12
3/16	0.187 and up	..

Flame

A slightly reducing (carburizing) flame is recommended with a slight excess of acetylene. A soft flame is preferable to the harsh or wild flame that results if too small a tip is used.

Fluxes—Application and Removal

Fluxes are required for gas welding Monel and Inconel but nickel does not require a flux. Since proprietary fluxes are recommended, the manufacturer should be consulted.

Borax is not recommended as a flux.

The flux protects the metal from oxidation or dissolves oxide and improves the fluidity of the molten metal. Flux is used preferably as a thin paste, made by mixing the dry flux with alcohol or dissolving it slowly in very hot or boiling water in the case of Monel, and with a thin orange shellac-alcohol solution (in the ratio of 1:5) for Inconel. The flux is applied with a small brush or acid swab, on both sides of the seam, top and bottom, and on the welding rod also.

Since the flux for Inconel contains fluorides, good ventilation should be provided for the welding operator.

The recommended fluxes are not corrosive and need not be removed after welding on that account. However, it is usual to remove them as a matter of cleanliness. This is done easily for Monel by dissolving the spent flux in warm water, and for Inconel either by sand blasting or by immersion in 50% (by weight) nitric acid solution for 5 to 10 min. at room temperature, followed by a water rinse.

Joint Design

Corner welds and lap joints may be used where high stresses are not encountered. In such equipment as pressure vessels, butt joints are preferred for gas welding since stresses act axially rather than eccentrically as in lap joints.

For butt joints in material of 0.050 in. to $^{5}/_{32}$ in. thick, beveling is not required. For vee butt joints in thicker metal, the sheet and plate edges should be beveled to an angle of $37^{1}/_{2}°$ to form a welding groove of 75°.

For sheet 0.043 in. and lighter, both butt and corner edge welds are used. Corner welds can be made by oxyacetylene welding in thicknesses of 0.037 in. and heavier.

Tube joints are made preferably by oxyacetylene welding, since a great deal of position welding of thin-walled (0.049 to 0.125 in.) and small diameter ($^{1}/_{2}$ to 5 in.) tubing is involved.

Jigs and Clamps

Reference should be made to Chapter 32C for a discussion of principles of jigging and clamping for welding.

Welding Technique

Usually the same size tip, or one size larger than that recommended by the torch manufacturers for similar thickness of steel may be used.

During welding, the end of the welding rod should be kept always well within the protecting flame envelope; this prevents oxidation of the hot rod. The tip of the luminous cone should contact the surface of the pool of molten metal to obtain a concentrated heat and to prevent oxidation. Gas welding goes along easily; Monel flows freely from the filler rod into the joint, nickel a little sluggishly and Inconel neither sluggishly nor very fluidly. Gas welds in Monel, nickel or Inconel, either in the as-welded or ground and polished conditions, are free from porosity.

Preheat

No preheating is needed for oxyacetylene welding wrought Monel, nickel or Inconel.

Heat Effect of Welding

As with electric-arc welding, there is no detrimental effect on the parent metal from the heat of gas welding.

Cleaning and Finishing Welds

Oxyacetylene welds usually are left in the as-welded condition, except that with Monel and Inconel the gas-welding flux is removed as described in the paragraph on Fluxes, above. Welds may be ground and polished if required.

Resistance Welding

Spot, seam and flash welding, all included under the term resistance welding, are applicable to the joining of Monel, "K" Monel, nickel, "Z" Nickel and Inconel. Typical examples of resistance-welded parts are: spot-welded Monel commercial laundry machines, seam-welded Monel hot-water boilers, flash-welded Monel chains and spot-welded nickel internal parts of radio tubes.

The fundamental principles of the resistance welding of plain low-carbon steel, to be found in Chapter 9, apply also to the joining of the high-nickel materials, with some slight modifications necessitated by their individual characteristics. Builders of resistance-welding equipment should be consulted regarding electrical requirements for specific applications.

The melting points of all five materials are of the same order, but differences in electrical resistivity and thermal conductivity are quite large. The heat for welding Monel and Inconel is obtained easily because of their higher electrical resistance and, since their thermal conductivity is correspondingly somewhat low, the dissipation of heat from the joint is restricted. Nickel, which has about the same electrical resistivity and thermal conductivity as mild steel, is spot welded quite satisfactorily also.

Spot* and Seam Welding

Monel, "K" Monel, nickel, "Z" nickel and Inconel can be joined by spot and seam welding, not only to themselves and to each other, but also to various other materials including the following:

Brasses
Bronzes
Cupro-nickels (70 Cu-30 Ni and 80 Cu-20 Ni)
Nickel silvers
Steel
Stainless steels.

The following variables require attention.

Pressure
Current

* Detailed data are to be found in "The Spot Welding of Nickel, Monel and Inconel," by W. F. Hess and A. Muller, *Welding Journal*, October 1941.

Time
Electrode material
Size and shape of the electrode.

Pressures are employed for nickel and high-nickel alloys which approach those used for stainless steel and are therefore higher than for carbon steel. The lower limit of pressure is fixed by weld soundness and the upper limit by objectionable sheet distortion. Optimum welding conditions produce joints with a nugget or fused weld of from 50 to 80 per cent of the thickness of the joint where the thickness of the two sheets are equal, and of about the thickness of the thinner of two sheets of unequal thicknesses.

The recommended times, pressures, and currents for various gages of annealed Monel, nickel and Inconel sheet are given in Table 11. Mechanical properties of spot welds in these materials are to be found in the same table.

In "setting" a spot-welding machine in which pressure has been adjusted, the current should be increased for succeeding welds until "spitting," or expulsion of metal, occurs, and then decreased to a point where expulsion no longer occurs. The spot-weld strength is then near the optimum. Excessive current may cause serious loss of weld quality due to severe internal cracking and porosity and may even fuse the exterior surface of the sheet; excessive indentation may be observed also. Insufficient current may only "stick" the sheets together.

Accurate control of the firing time is essential to the production of uniform welds since the energy delivered must be in rather narrow limits if consistent fusion and strength are to be obtained. Thyratron, Ignitron and smaller vacuum tube timers serve the purpose well.

Water-cooled, copper-alloy electrodes, that are harder than ordinary copper and have less tendency to mushroom under continuous service, are recommended.

Flat tips are used in preference to dome tips. Tip diameters suitable for the high-nickel materials range from $^1/_8$-in. for 0.025-in. sheet, $^1/_4$-in. to $^5/_{16}$-in. for material 0.062-in. thick, to $^3/_8$-in. to $^1/_2$-in. for 0.125-in. sheet. Some indentation will be produced which may not be objectionable. On finished surfaces, where depressions would be unsightly, a polished, flat, copper electrode, about 2-in. square, $^1/_4$-in. to $^1/_2$-in. thick, should be used against the side of the joint that is to be finished.

Visual examination of the surface of a spot or seam weld will not disclose the quality of the weld. A quick method of sectioning and examining welds which has proved very satisfactory in connection with machine adjustment and weld evaluation consists of scribing a line across the center of the weld, shearing or sawing adjacent to the center of the weld, smoothing this cut by filing or grinding to the center of the line, and then macro-etching the section produced. Visual examination of the section shows diameter, penetration, structure and gross flaws. If the strength-diameter relation is known for a particular case, the approximate weld strength may easily be predicted from its dimensions. The length of time necessary to perform this test is in the neighborhood of two minutes. The "quick section" test is of much greater value than the "peel" test as a method of setting up machines in the shop.

Table 11—Data for Spot Welding Monel, Nickel and Inconel Sheet

Metal Thickness, In.	Flat Face of Electrode Diam., In.	Electrode Shape	Total Electrode Pressure, Lb.	Unit Electrode Pressure, Psi.	Firing Time, Cycles	Current, Amp.	Strength per Spot, Lb.
Recommended Conditions for Spot Welding Monel Sheet							
0.021	1/8	30° bevel	184	15,000	12	6,200	570
0.032	3/16	30° bevel	690	25,000	12	10,600	1,290
0.062	5/16	30° bevel	2685	35,000	12	20,700	3,930
	1/4	30° bevel	1962	40,000	12	15,300	3,215
0.093	3/8	30° bevel	2765	25,000	20	22,600	6,300
	5/16	30° bevel	2685	35,000	12	20,000	4,370
0.125	1/2	30° bevel	4910	25,000	30	30,800	10,950
	3/8	30° bevel	3870	35,000	30	21,300	7,800
	3/8	30° bevel	4420	40,000	20	23,900	6,825
Recommended Conditions for Spot Welding Nickel Sheet							
0.021	1/8	30° bevel	245	20,000	4	7,760	445
0.032	3/16	10° bevel	829	30,000	4	15,400	950
	1/8	30° bevel	429	35,000	4	9,200	740
	1/8	10° bevel	490	40,000	4	10,000	720
0.062	5/16	30° bevel	2685	35,000	6	29,000	3,190
	1/4	30° bevel	1720	35,000	6	21,600	2,855
0.093	3/8	30° bevel	2765	25,000	12	32,000	5,825
	5/16	30° bevel	2305	30,000	12	26,400	5,015
0.125	3/8	10° bevel	3315	30,000	20	33,700	8,600
	3/8	30° bevel	3315	30,000	20	30,800	8,750
Recommended Conditions for Spot Welding Inconel Sheet							
0.021	1/8	30° bevel	184	15,000	12	4,040	700
0.032	3/16	30° bevel	690	25,000	12	6,710	1,485
	1/8	30° bevel	368	30,000	12	3,730	1,040
0.062	5/16	30° bevel	3070	40,000	12	12,000	4,340
	1/4	30° bevel	2455	50,000	12	9,300	3,380
	1/4	30° bevel	1962	40,000	20	6,100	3,365
0.093	5/16	30° bevel	3070	40,000	20	12,700	6,350
	3/8	30° bevel	3870	35,000	20	15,000	7,125
0.125	7/16	30° bevel	5270	35,000	30	20,100	10,525
	1/2	30° bevel	5900	30,000	30	21,500	12,000

Flash Welding

Flash welds may be made in Monel which will develop the full strength of the annealed material.

Energy input is necessarily greater for Monel than for steel because the resistivity of Monel requires higher secondary voltages to produce the necessary current. The amount of upset should be sufficient to eliminate completely molten metal from the weld. Any further upset is unnecessary and results in forming cold metal which may distort the joint. It is essential that the push-up be started immediately before the current is interrupted to obtain the best welds. Push-up should come during the last two cycles of current flow. If it comes after the current cut-off there is likely to be some trapped cast metal in the weld as well as trapped oxide. If much longer than two cycles of current is passed after push-up, the metal will be overheated during this butting condition with pinholes and

intergranular melting as a result. The welds produced may be of poor quality and lowered strength.

It is necessary that Monel be trimmed accurately to leave a very uniform gap between the two sheets. If this gap is not uniform the parts that are close together develop more heat and may possibly burn when flashing, while the parts that are far apart will not get enough heat to weld during the push-up. With comparatively heavy section such as round rods, the material may be pointed to permit flashing to start easily. This permits flashing to proceed with the minimum energy input. Too high a flashing energy results in violent short circuits which remove too much material and leave long time intervals between successive flashes. Fine, rapidly-recurring flashes result in the most uniform heating and best weld quality. If heavy sections are not pointed in preparation for flashing, it will be necessary to use high energy input to start the flashing without butting of the pieces.

Dies used for clamping Monel for flash welding should be spotted accurately and must fit as snugly as possible to keep the material from slipping or arcing during a push-up. The close fitting of the dies also holds the two pieces of Monel tightly so that one sheet will not overlap the other during burning off and pushing up. Current is usually fed to the metal from both welding jaws. It is virtually a necessity in the case of round sections where the limited area of contact provided by only the lower jaws tends to result in high current density at the edge of the dies. If current is introduced only through the lower die, the high-current density may be sufficient to melt Monel or Inconel at the edge of its contact with the dies. These "die burns" are usually cracks which are caused by the over-heated metal tending to crack on cooling. Naturally die burns will reduce the strength of the welded joint owing to stress concentrations.

The following table contains typical flash welding conditions for $^3/_8$-in. hot rolled rods in several of the high nickel alloys.

Table 12—Flash Welded Joints in Rod

Rod diameter—$^3/_8$-in.
Rod preparation—pointed—110° included angle.
Current cut-off—two cycles after upset begins.

Material	Flashing Distance, In.	Upset Distance, In.	Flashing Time, Sec.	Weld Strength, Psi.	Rod Strength, Psi.
"A" nickel	0.450	0.140	2.5	63,000	63,500
Monel	0.450	0.140	2.5	82,200	84,700
"K" Monel	0.450	0.140	2.5	98,000	99,000
Inconel	0.450	0.140	1.8	103,000	106,000

The best welds will be obtained with machine settings adjusted to give the minimum value which will result in complete flashing. Any lower setting will result in butting and unsatisfactory welds. Higher settings, as mentioned above, will result in oxidized welds.

The above welds were made with a cam providing uniformly accelerated motion. This permits easy starting on cold metal and provides rapid flashing just prior to upset, which minimizes the tendency to trap oxides.

Submerged Melt Welding

Monel and nickel have been welded successfully by the submerged melt welding process using essentially the same procedures and speeds as are used with similar thicknesses of steel. Tests of joints in both Monel and nickel have shown that satisfactory tensile strength, ductility and impact properties are obtained in the welded joint and also in the deposited metal. Tests of the fatigue strength of these welds in both Monel and nickel plates have given high values comparable to the fatigue strength of the parent materials.

The average mechanical properties of test welds made in $^1/_2$-in. plates in a single pass at a speed of 18 in. per minute for Monel, and at a slightly lower speed for nickel, are given in Table 13.

Table 13—Mechanical Properties of Submerged Melt Welds in ½-In. Plate

Material	Yield Strength (0.20% Offset), Psi.	Tensile Strength, Psi.	Elongation in 2 In., %	Reduction of Area, %	Charpy Impact Strength, Ft.-Lb.
Monel					
All-weld metal specimens	26,600	62,400	46.0	59.0	42
Reduced transverse weld specimens	36,900	70,300	45.0	..	..
Fatigue strength (10,000,000 reversals at 6000 rpm. in Krouse test), 34,000 psi. Elongation in free bend, 50%					
Nickel					
All-weld metal specimens	16,800	55,200	33.0	44.0	56
Reduced transverse weld specimens	28,000	55,600	21.0	..	..
Fatigue strength (10,000,000 reversals at 6000 rpm. in Krouse test), 29,500 psi. Elongation in free bend, 45%					

Atomic-Hydrogen Welding

With nickel and nickel alloys, the usefulness of atomic-hydrogen welding has been limited to the automatic production of welded Inconel and Monel tubing with wall thicknesses of about 0.018 to 0.050 in. A uniform penetration is obtained with a flat outer surface; no filler rod is added. The process offers no advantages over oxyacetylene or metal-arc welding, or silver brazing, for routine fabrication of equipment.

Bronze or Brass Brazing

The usefulness of Tobin Bronze and other bronze welding rods for brazing nickel, Monel and Inconel is very limited because the corrosion resistance of bronze joints frequently is not of the same order as that of the metals being joined. In general, bronze welding rods are useful only for the fastenings where corrosive media would not come in contact with the joint.

Brazing is used in joining Monel or nickel-clad steel bottoms to copper varnish kettles.

Furnace Brazing

In furnace brazing parts are assembled and held in place mechanically, with the brazing material, either a silver solder or copper, placed in position so that it will flow into the joints when the parts reach the brazing temperature in the furnace having a reducing atmosphere. Heating should be done rapidly and uniformly. Furnace temperatures are maintained usually at 1250 to 1400°F. for silver-brazing alloys, and at 2000 to 2100°F. for copper brazing.

For details of the process, reference should be made to the Furnace Brazing portion of Chapter 14D.

Because of the readiness with which it alloys with nickel and nickel-copper alloys, copper does not penetrate into lap joints very satisfactorily when it is introduced in the usual manner, that is, by placing a copper wire at the edge of the joint and having the molten copper flow through by capillary attraction on heating. A better procedure for the high-nickel materials is to introduce the copper as a thin plating or as a thin foil up to a few thousandths of an inch in thickness. On heating the assembly with either the plated copper or the inserted foil, a uniform bonding is obtained over the full length of the joint.

Carbon Arc Welding

Carbon arc welding, although no longer generally recommended, can be used successfully for the welding of intermediate gages (0.037 to 0.062 in.) of Monel and nickel. The method is superior to oxyacetylene or electric-arc welding in that it is possible to obtain a neat joint in the gages mentioned with a minimum of reinforcement with little distortion; for example, in manual circumferential welding of tubing, where welds must be ground and finished, less grinding is involved in carbon arc welds than by other joining methods. With the advent of the improved metal arc-welding electrodes now in use the need for carbon arc welding has practically ceased to exist.

Flame Cutting

Oxyacetylene flame cutting is not recommended for Monel, nickel and Inconel because the results obtained are crude and unsatisfactory. Mechanical methods of cutting such as machining, shearing, punching and nibbling are recommended.

Joining "K" Monel

"K" Monel can be welded by either the oxyacetylene or the metal-arc process using the rods mentioned below. After age-hardening, the properties of the weld, naturally, are not as high as those of the parent metal, since the welded joint is not subjected to cold work. Like the parent metal, however, the weld is non-magnetic.

Silver brazing may be used in joining "K" Monel, and assemblies so made are amenable to age-hardening. Soft soldering also is practical but rarely used. A soft-soldered joint obviously could not be age-hardened, so that if hardening is required it must be carried out before the soft soldering is done. Any visible oxide film on the age-hardened parts should be removed mechanically or chemically before soldering.

In general, the instructions recommended for joining Monel are to be followed, with the exceptions noted in the paragraphs that follow.

Metal-Arc Welding.—The same joint designs and welding procedures used for Monel are applicable to "K" Monel. A "K" Monel Welding Electrode should be used. Weld metal deposited with this shielded-arc electrode in "K" Monel plate can be hardened, and is sound and non-magnetic.

Tensile tests of joints, in the as-welded and age-hardened conditions, in $^1/_8$-in., $^1/_4$-in. and $^3/_8$-in., soft "K" Monel plate welded with "K" Monel electrodes, have been given in Table 5.

Similar welds made with Monel electrodes were equally sound but gave only a slight increase in strength and hardness following the age-hardening treatment.

Oxyacetylene Welding.—The oxyacetylene flame should be strongly reducing.

A flux, to protect the molten weld metal from oxidation, must be used as a thin paste painted on the top and the under side of the joint to be welded, and on the "K" Monel filler rod.

"K" Monel Gas-Welding Wire should be used as filler material.

Gas welds as laid down have about the same hardness as cast "K" Monel, approximately zero Rockwell C, but are amenable to the usual age-hardening treatment for wrought "K" Monel by which hardness levels of the order of 20 to 30 Rockwell C can be obtained.

Joining "Z" Nickel

"Z" nickel can be welded by the electric-arc and oxyacetylene processes, silver brazed and soft soldered with the same facility as nickel. Soft-soldered joints are used rarely because, as for "K" Monel, it is not possible to age-harden the assembly without melting the solder. Previously age-hardened material can be soft soldered. Welded or silver-brazed joints in "Z" nickel can be age-hardened, but the welds, which are made with nickel welding wires, will not respond to thermal treatment. The joints however, are ductile and strong. It is practical to silver braze "Z" nickel after age-hardening with very minor effect on the hardness of the parent metal.

The procedures set forth for joining nickel are recommended for "Z" nickel also.

Joining Dissimilar Metals

Soft soldering, silver brazing and welding can be used for joining dissimilar metals. The process selected depends on the conditions to be encountered in service. If a material can be soft soldered or silver brazed readily, then, other things being equal, it can be joined to Monel, nickel or Inconel by these methods.

Welding is used widely for joining Monel, nickel or Inconel to other materials. The most frequently used combinations are Monel-to-steel and the welding of nickel-to-steel in certain types of nickel-clad steel fabrication. For both types of joint, Monel welding electrode should be used.

In electric welding dissimilar metals, it is essential that penetration be kept to a minimum. Therefore, excessive welding currents and puddling must be avoided.

Combinations that have been welded or brazed successfully are listed in Table 14.

Table 14—The Joining of Dissimilar Metals

Material			
Base	Joined to	Method	Welding Rod and Flux
Plain carbon steel	Monel Nickel Inconel	Metal-arc welding	Monel welding electrode Monel welding electrode Inconel welding electrode or 18–8 stainless electrode
	Monel Nickel Inconel	Oxyacetylene welding	Monel gas-welding wire and a flux Monel gas-welding wire and a flux Inconel gas-welding wire and a gas-welding flux
	Monel Nickel Inconel	Silver brazing	Silver-brazing alloy and flux
	Monel Nickel Inconel	Soft soldering	Soft solder and flux
18–8 Stainless steel	Monel Nickel Inconel	Metal-arc welding	Not recommended Inconel welding electrode or 18–8 stainless electrode Inconel welding electrode
	Monel Nickel Inconel	Oxyacetylene welding	Not recommended Inconel gas-welding wire and a flux Inconel gas-welding wire and a flux
Monel	Galvanized steel Nickel Inconel	Metal-arc welding	Monel welding electrode (not necessary to remove galvanizing) Monel welding electrode Monel welding electrode
	Nickel Inconel Copper	Oxyacetylene welding	Monel gas-welding wire and a flux Monel gas-welding wire and a flux Brass brazing rod and flux or by silver solder
	Silicon-copper	Carbon-arc welding	Silicon-copper welding rod and silicon-copper welding flux
Nickel	Inconel	Metal-arc welding	Nickel welding electrode
	Inconel Copper	Oxyacetylene brazing	Inconel gas-welding wire and Inconel gas-welding flux Brass brazing rod and flux or a silver-brazing alloy
	Silicon-copper	Carbon-arc welding	Silicon-copper welding rod and silicon-copper welding flux
70–30 Cupro-nickel	Carbon steel	Metal-arc welding	Monel welding electrode
Copper	Carbon steel	Metal-arc welding	Monel welding electrode. The copper must be preheated.

Hard-Surfacing Overlay on Monel, "K" Monel, Nickel and Inconel

A number of abrasion-resistant, hard-surfacing alloys can be applied readily to Monel, nickel, Inconel and "K" Monel with the aid of the oxy-acetylene welding torch. Colmonoy and Stellite are materials that have been used for hard-surface overlays. The Colmonoy alloys are composed of complex mixtures of very hard chromium-boride crystals in a matrix of pure nickel. Melting points of the alloys are very close to 1865°F. Varying hardnesses are obtained by controlling the proportions of boride crystals and nickel; for example, a composition containing approximately 69% nickel, balance crystals, has a hardness, as deposited, of 45 to 55 Rockwell C. The high-nickel contents of the Colmonoy hard-surfacing materials make them very useful for resistance to abrasion in corrosive environments.

Stellite cobalt-chromium-tungsten alloys melt at temperatures from 2282 to 2327°F. They have good gas-welding properties. They are available in several grades to meet the requirements of all hard-facing applications.

When applying Colmonoy and Stellite, the base metal temperatures should be only slightly above the melting point of the hard-surfacing material to avoid boiling and formation of holes in the hard-surfaced overlay.

Welding of Castings

Monel, nickel and Inconel castings can be joined either to themselves or to wrought forms of these materials by oxyacetylene or electric-arc welding or by silver brazing. The sand-cast surfaces must be removed from the areas to be joined, either by rough grinding or machining. The welding and brazing procedures used for the wrought forms can be applied without change to castings and will produce pressure-tight joints.

The high silicon casting alloys—"H" Monel and "S" Monel—are quite hard, and possess good non-galling characteristics. Minor surface defects can be repaired by following the welding instructions given for Monel. Joining of "H" Monel or "S" Monel castings by welding is not recommended because of a definite tendency toward cracking of the castings. Only mechanical joints should be used in these materials.

Cleaning for Maintenance Welding

Before doing any repair or maintenance welding on Monel, nickel, Inconel or clad steel plate that has been in service, it is necessary to remove products of corrosion, and any other foreign material, from the vicinity of the area to be welded. Great care should be taken to get down to clean, bright, parent metal over an area extending 2 to 3 in. from the site of welding and on both sides of the sheet or tube. The corrosion products might have an embrittling effect on the high-nickel material at welding temperatures. Cleaning mechanically, by grinding with either a fine wheel or a disc grinder, or chemically, by pickling, is recommended. After cleaning, the welding procedures outlined previously for new metal should be followed in every detail.

Overlaying Monel and Nickel on Cast Iron, Cast Steel and Carbon Steel

Overlaying with, or the deposition of, a layer of Monel or nickel on cast iron, cast steel and carbon steel plate is accomplished readily by metal arc welding. Although overlaying with Monel and nickel is done largely with an electric arc, the oxyacetylene method can be used also. The instructions regarding polarity, arc length and electrode position given for electric welding of Monel and nickel should be followed with the addition of those given below.

Cast Iron, Cast Steel and Wrought Carbon Steel.—Overlaying Monel on cast iron, cast steel and mild steel is done with Monel electrodes $^1/_8$ in. and $^5/_{32}$ in. diam. to obtain minimum iron dilution in single layers. Larger electrodes, $^3/_{16}$ in. and $^1/_4$ in. diam., can be used for following layers in building up thick overlays.

The first layer of weld metal should be deposited in a series of narrow beads, to avoid excessive penetration.

Preheating to 500 to 700°F. is beneficial when the overlaying is to be done on castings of thin cross-section. On heavier castings also, preheating is beneficial though not essential and when possible such castings should be preheated. When preheating is impractical, large castings should be permitted to cool to 140 to 150°F. after each welding pass.

Monel overlays on cast iron and cast steel, deposited with Monel electrodes have hardness values of 150 to 160 Brinell (3000 kg.). Nickel overlays on plain carbon steel deposited with the nickel electrode have hardness values of 140 to 150 Brinell (3000 kg.) for single layers and about 125 Brinell for two or more layers.

Thermal Treatment of Welded Vessels

Since the corrosion resistance of Monel, nickel and Inconel is inherent, heat treatment after welding is not necessary for the restoration of corrosion-resisting properties. The heating of welded vessels of Monel, nickel and Inconel for relief of stresses set up because of the welding operation may be called for in special instances but in general it is not recommended. This is because these materials are highly ductile in both plate and weld metal and, in the range of plate thicknesses under $^3/_4$ in. normally encountered in vessel construction, do not require a heat treatment for the accommodation of welding stresses.

When a stress-relief heat treatment is specified to fulfill a Code requirement, the time and temperature recommended are those used for steel vessels, namely, 1100 to 1200°F. for one hour per inch of thickness. Code requirements should be followed in other details also, and particular care should be given to supporting the vessel in all directions so that it will not be distorted during heating.

Grinding and Finishing Welded Joints

Monel, nickel and Inconel welds that are not to be used in the as-welded condition can be rough ground and finished easily. Usually, finishing is necessary in the case of food handling and other processing equipment in which smooth, sanitary surfaces are required.

Inspection

X-Ray Examination.—Exographs of properly welded joints, by either the electric-arc or the oxyacetylene process, in Monel, nickel or Inconel, and by the submerged melt process in Monel or nickel, are acceptable according to the standards set for steel by the A.S.M.E. Code for Unfired Pressure Vessels.

Etching Solutions for Welds.—Polished sections of welded joints can be etched readily to disclose the weld and parent metal structures by immersion for 5 to 10 sec. in the following etchants: (*a*) for Monel, a cold solution of equal volumes of water and concentrated nitric acid; (*b*) for nickel, cold concentrated nitric acid; and (*c*) for Inconel, warm aqua regia after first warming the specimen in hot water. If the Inconel weld does not etch readily, a small amount of cupric chloride may be added.

Silver Brazing

Silver brazing is the term now used instead of the older names, "silver soldering" and "hard soldering." It is defined as "a brazing process wherein a silver alloy is used as a filler metal." Reference should be made to the chapter on Silver Brazing for fundamentals of the process.

Brazing Alloy and Flux

Silver-brazing alloys flowing at less than 1400°F. are best for joining high-nickel materials. These are essential for Monel which is subject to intergranular attack by molten brazing alloys and failure, if under even low stress at temperatures of 1400°F. or higher. Monel is not subject to attack when temperatures below 1400°F. are maintained during brazing operations. A suitable composition is "Easy-Flo"(50% silver, 15.5% copper, 16.5% zinc and 18% cadmium) which melts at 1160°F. and flows at 1175°F. "Handy Flux" is used with this brazing alloy. Borax and boric acid fluxes are not useful for silver brazing because they are not fluid at the temperature levels recommended and hence are not protective.

Joint Design

Shear- (lap-) type joints are used more widely than butt joints because of the ease of maintaining better fits and the facility wherewith adequate strength can be obtained merely by extending the lap-shear area. Typical joints for silver brazing Monel, nickel and Inconel are shown in Fig. 4.

Brazing Procedures

Cleaning.—All foreign material must be removed from the parts before assembly. Any dark-colored oxide layer resulting from heating, as in annealing, must be removed either mechanically, with emery cloth or by light, fine grinding, or chemically by pickling.

Flux usually is mixed to a thin paste with water and applied by brushing a thin film over the surfaces to be joined. The flux prevents oxidation during heating, dissolves oxides formed during brazing and assists in "flowing-out" the brazing alloy.

Heating.—Any of the usual methods of heating the parts to be silver brazed may be employed for Monel, nickel or Inconel.

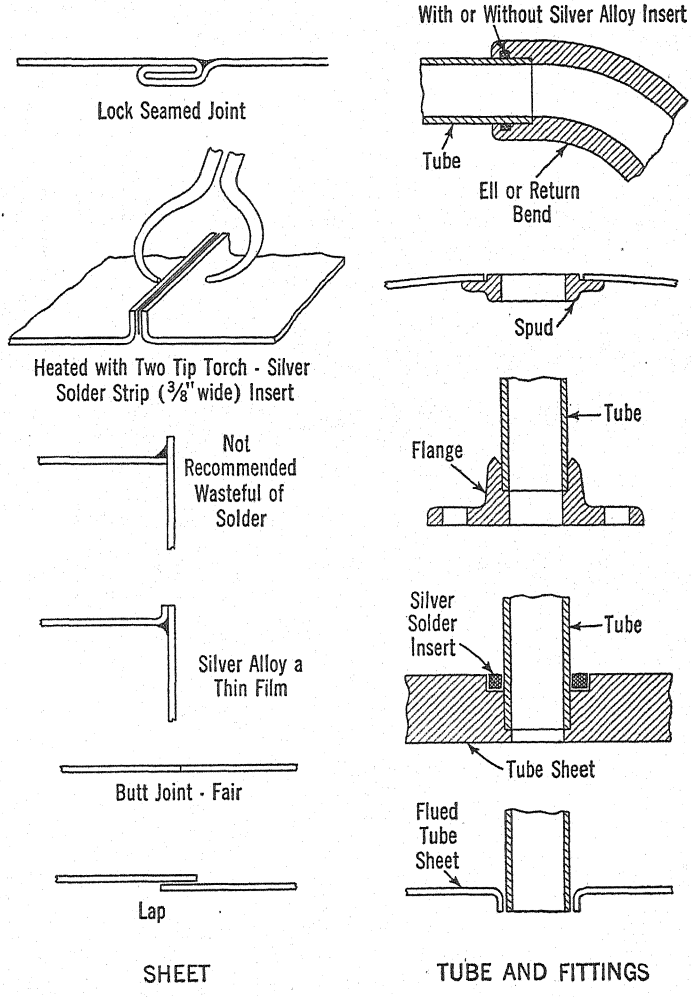


Fig. 4—Joints Used for Silver Brazing Monel, Nickel and Inconel

Heat Effect of Brazing

Since the temperatures required for joining with silver brazing alloys are well below those for annealing Monel, nickel and Inconel, the softening effect of brazing is very slight. Age-hardened "K" Monel or "Z" nickel parts are silver brazed with only a slight local softening using Easy-Flo brazing alloy. Age-hardening of "K" Monel or "Z" nickel may be carried out after silver brazing.

Figure 5 shows a photomicrograph of a lap joint in Monel made with "Easy-Flo" brazing alloy.

Sil-Fos, although an excellent brazing material for brass and copper, is not recommended for use on Monel, nickel or Inconel because of an em-

brittling effect of the phosphorus constituent. Phosphor-copper, which contains no silver, is unsuitable for the same reason.

Cleaning Brazed Joints

The spent flux, remaining after a joint has been silver brazed, is removed by dissolving it in hot or cold water.

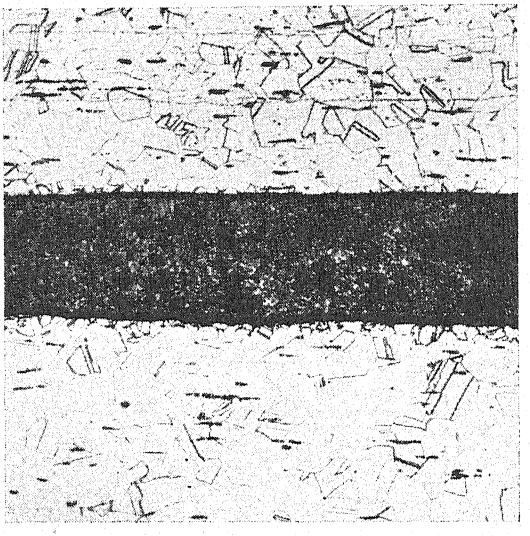


Fig. 5—Photomicrograph (100 ×) of Silver-Brazed Lap Joint in Monel. Etched with 50% Nitric Acid Plus 50% Glacial Acetic Acid

Soft Soldering

Soft soldering as a means for joining the high-nickel materials is limited to those applications where the solder is not corroded readily. Soft solder is inherently weak, and dependence for strength must be placed usually on mechanical joints, such as riveted, lock-seamed or spot-welded joints, with the soft solder acting only as a sealing medium. The process is limited usually to joints in sheet metal not more than 0.062 in. thick because other processes yield stronger joints in these and heavier gages.

Mechanical Properties of Soldered Joints

Compared with the strength of the sheet material, a soldered joint is weak. The results of strength tests of soft-soldered lap and lock-seamed joints in Monel, following normal roofing practice, are given in Table 15. A 50–50 lead-tin solder was used both with a proprietary (prepared) flux and with "cut acid."

Failure of the lap seams occurred usually by rupture in tension of the parent metal, but in some cases by rupture in shear of the soldered joint. All lock-seamed joints failed by tearing of the solder fillet.

Table 15—Tensile Strength of Soft-Soldered Joints in Monel Sheet of Roofing Quality—Sheet Edges Pretinned

Joint	Flux	Specimen Width, In.	Tensile Strength of Joint (Average of 3 or More Tensile Specimens), Lb.
1/4-in. lap	Cut acid	1	1204
1/4-in. lap	Cut acid	2	2213
1/4-in. lap	Prepared flux	1	1253
1/4-in. lap	Prepared flux	2	2153
1/2-in. lap	Cut acid	1	1377
1/2-in. lap	Cut acid	2	2650
1/2-in. lap	Prepared flux	1	1443
1/2-in. lap	Prepared flux	2	2682
5/8-in. lock seam*	Cut acid	1	977
5/8-in. lock seam*	Cut acid	2	2363

* Both surfaces of the two sheets comprising the joint were pretinned.

Solders

The composition and melting point of soft solders commonly used on corrosion-resisting equipment are given in Table 16. Of these, the 50–50 and the 60–40 tin-lead solders are used most widely. The trade uses the 60–40 rather than the 63–37 (eutectic) composition. Pure tin is justified only where corrosion conditions demand its application.

Table 16—Melting Point and Shear Strength of Commonly Used Soft Solders*

Material	Temperature, °F.		Shear Strength, Psi.
	Complete Liquefaction	Complete Solidification	
Pure tin	450	450	2865
63–37 tin-lead	359	359	6230
50–50 tin-lead	414	359	5740
40–60 tin-lead	460	359	4975

* International Tin Research and Development Council.

Fluxes

Only those soft-soldering fluxes known in the trade as "acid" fluxes are recommended for use with Monel, nickel or Inconel. Rosin is not suitable since its cleaning action is too mild. The proprietary or "cut acid" fluxes commonly used for copper are adequate for the soft soldering of Monel and nickel, but a somewhat stronger flux is required with Inconel because of its chromium oxide film. In general, proprietary soft-soldering fluxes are to be preferred.

All traces of flux should be removed after the soldering operation has been completed.

Joint Preparation

Surfaces of metal parts to be soft soldered must be clean and free of any surface oxide or other discoloration. Foreign material, such as oil, grease or dirt, must be removed. Oxide or other tarnish can be removed mechanically with emery cloth or by light grinding, or chemically by pickling. Wherever possible, the surfaces to be joined should be "pretinned"

to insure complete bonding during the final soldering or "sweating-in" operation. "Pretinning" is done with the solder to be used for the joint and not necessarily with pure tin as the term would seem to indicate. With untinned edges the solder may not penetrate throughout the joint.

The Soldering Operation

The heat for soldering is supplied by a soldering "iron" (actually copper), a gas-air torch or an oxyacetylene torch. Because the transfer of heat through the high-nickel materials is slower than through copper, it is necessary to use either a hotter or a slightly larger soldering "iron" than that regularly used for similar work with copper sheets.

III—HIGH-NICKEL-CHROMIUM-IRON HEAT-RESISTING ALLOYS

There are a number of nickel-chromium alloys which are used primarily as heat-resisting alloys in such applications as the heat treatment of steel, carburizing, enameling, glass making and other high-temperature applications.

Only those alloys containing 50% or more nickel are discussed in this chapter, namely:

(*a*) 65–68% nickel and 15–19% chromium (Alloy Casting Association Designation HX).

(*b*) 59–62% nickel and 10–14% chromium (Alloy Casting Association Designation HW).

(*c*) 80% nickel and 12 to 20% chromium.

These materials, both in cast and rolled forms, are known by many trade names. They are not only non-carburizing, but also have a characteristic non-flaking scale.

Of especial interest are the wrought forms of these alloys, i.e., sheet, plate, rod, tube or bar stock. Open welded carriers, used in carburizing and annealing, built of wrought materials are lighter and have higher ductility than equivalent cast carriers. The welded baskets hold metal parts in their travel through continuous carburizing or annealing furnaces at temperatures up to 1750°F., after which both the basket and its contents are quenched in either oil or water. These baskets are welded by oxyacetylene, electric-arc, or atomic-hydrogen welding.

Sheet metal is used for welded carburizing boxes and other fabricated high-temperature furnace parts.

The wrought material is joined by welding employing the oxyacetylene, electric-arc, or atomic-hydrogen processes. Since the materials are furnished usually in hot-rolled form, a thin darkly colored oxide covers them. Good welding practice dictates that the oxide film be removed from the immediate vicinity of the area to be welded either mechanically by machining, sandblasting, grinding or rubbing with coarse emery cloth, or chemically by pickling. Light grinding, either with fine-grit solid emery wheels, emery discs or rolled head wheels, is employed most frequently. Difficulty in the form of a wandering arc in arc welding, and difficulty in melting through the oxide film in flame welding, is encountered if the oxide is not removed.

In oxyacetylene welding, a flux may or may not be used, though a flux is beneficial in keeping the chromium oxide from forming and being a disturbing element. The flame should be very slightly reducing. Welding rods, either drawn or cast, but of the same general composition as the metal being welded, are used as filler rods. Cast welding rods should have removed from their surface such foreign materials as molding sands.

Flux-covered welding electrodes are made in the same general compositions as the wrought material. These are all reversed polarity electrodes.

In joining these materials, practices for fitting up and welding employed for high-quality steel fabrication are used without important change. Since the coefficients of expansion of the alloys containing 59 to 68% nickel are appreciably higher than steel, expansion and contraction must be taken into account if excess buckling is to be avoided. The heat-resisting alloys containing 80% nickel have a coefficient of expansion approximately the same as steel.

IV—WELDING HASTELLOY ALLOYS

Hastelloy alloys A, B and C can readily be welded by the oxyacetylene, metallic arc or atomic-hydrogen process and strong, corrosion-resistant welds obtained. The carbon arc cannot be used because of carbon pickup and consequent lowering of corrosion resistance.

Preheat

Localized preheating is sufficient when welding small castings of Hastelloy alloys A, B and C; but for large castings, thorough preheating is advisable to prevent heating and cooling strains incidental to the welding operations. The size and shape of the part to be welded will determine whether preheating is necessary. No heat treatment of welded castings is necessary unless they have been preheated for welding and held at red heat for an appreciable period of time while the welding operations were being performed, in which case it would be necessary to fully anneal the casting after welding.

Welding

Cast Hastelloy alloy A, B and C parts are generally welded by the oxyacetylene process, using a neutral flame and a welding rod of the same composition as the base metal, with the exception that alloy A is usually welded with alloy B welding rod to give superior corrosion resistance in the welds. An excess acetylene flame is likely to increase the carbon content and impair the corrosion resistance of the weld metal. Therefore, precautions should be taken to maintain a neutral flame to prevent carbon pickup. A special flux supplied by the manufacturers of the Hastelloys facilitates the welding operations, although frequently its use is not necessary.

Welding of Hastelloy alloy A, B and C sheet and plate can be performed by either the oxyacetylene process with bare rod, or the metal-arc process with a flux-coated rod, while for large fabricated equipment the metal-arc welding is preferred. In electric welding, reversed polarity should be used

with the arc choked very short. Welding rod of the same grade as the base metal should be used with the possible exception of the welding of alloy A, where B rods may be used for superior corrosion resistance. Overheating of the weld metal is to be avoided, as this is apt to cause porosity. If porosity in the starting and stopping of the arc is encountered, it can be overcome by starting the arc on a tab adjacent to the seam and finishing off the arc on a similar tab.

The atomic-hydrogen process produces sound welds in the Hastelloy alloys when care is taken to prevent overheating. This type of welding is particularly adapted to automatic setups. In welding Hastelloy alloy C sheet, however, the metal-arc method is preferred as this alloy hardens alongside the weld more rapidly than either A or B. The atomic-hydrogen process develops considerable heat and keeps the metal in the hardening range for an appreciable time, resulting in distinct embrittlement, so that any severe tensile strains due to cooling after welding may cause cracking.

Annealing After Welding

When welding Hastelloy alloy A, B and C sheet and plate or Hastelloy alloy A and B hot-rolled bar stock or forgings, it is desirable to anneal after welding. In welding the wrought material, hardening may occur alongside the welds where the sheet is held in the hardening temperature range. This condition will cause accelerated corrosion in these areas, and to overcome this difficulty and impart maximum corrosion resistance to the plate, it is necessary to give a full anneal or a stabilizing anneal. If it is not possible to anneal after welding, the sheets can be obtained in the stabilized condition, which eliminates the necessity of heat treatment after welding, as the tendency for the stabilized alloy to harden is practically eliminated. Since stabilized sheets are not as ductile as fully annealed sheets, the former should be used only where severe forming operations are not required.

The alloys in sheet form can all be welded readily to steel, using either Hastelloy alloy electrodes or stainless steel electrodes such as Type 309. For composite equipment such as jacketed vessels, heat treating presents another problem, as the other metal used might not stand up under the high annealing temperature required for the Hastelloy alloys. This problem has been solved by welding Hastelloy alloy rings or rings of high-chromium steel, resistant to scaling at 2150°F., to the main body of the vessel before giving the vessel a full anneal. In the case of a steam jacket, the outside wall of the jacket itself can then be welded to the ring and no subsequent heat treatment would be required, since the weld between the ring and the jacket would not be subject to corrosion.

Hastelloy D

Hastelloy alloy D can be welded by the oxyacetylene process, using an excess acetylene flame and Hastelloy alloy D welding rod. Castings to be welded should be gradually preheated to a dull red heat and maintained at this temperature during the entire welding operation. They should then be slowly and uniformly cooled to room temperature in a furnace. Often satisfactory preheating can be arranged by building around the casting a temporary wall of loose insulating brick, open at the top and heated with

gas at the bottom. The castings should be supported in such a manner that they can be turned to make the necessary welds through the top while the entire castings are maintained at a uniform temperature.

V. WELDING ILLIUM

Illium was developed primarily as a material to be resistant to sulphuric, phosphoric and nitric acids over a wide range of concentration and exposure conditions. A description of the material is given on page 911.

Illium welds readily, both to itself and to other metals. When Illium welding rod is used, the structure of the weld is practically identical with that of the original casting.

Illium can be welded by means of either the oxyacetylene or electric arc process. Uncoated rod should be used for acetylene welding. Before welding, however, the casting should be preheated to 2200°F., allowing the entire casting to come up to this temperature uniformly and slowly. Welding operations should be done with a slightly reducing flame to avoid possible porosity in the weld. A neutral flame should not be used as it will cause the weld to crack as well as increase the size of the pits being welded. Upon completion of the weld, the torch should be withdrawn slowly, allowing the heat of the torch to keep off any cool air while the welded portion is cooling. If the torch is withdrawn immediately after the weld is completed, oxidation will take place and crater shrink results. Any good cast-iron flux is recommended for the welding of Illium, but one which is free of borax is preferable.

When electric arc welding Illium a flux-coated Illium welding rod should be used. Arc welding of Illium must be done with reverse polarity, that is, work negative, and electrode positive. The short arc, similar to that used in good steel practice, should be maintained. An electric weld cannot be puddled, as practiced with the torch, nor can it be reworked. The full weld cross-section should be deposited in one operation since metal laid on in layers and allowed to cool before applying the next, does not give a sound weld. In the arc welding of Illium, a minimum heat which will produce a weld should be used.

CHAPTER 25

LEAD AND ZINC*

Welding Lead with the Torch, Lead Pipes and Lead Linings, Wrought Zinc, Zinc-Base Die Castings

ZINC is torch welded with about the same technique as aluminum, whereas lead requires a specialized technique, often called lead burning†, utilizing no flux. Welding is an important process in constructing chemical apparatus of lead $^1/_{32}$ to over 1 in. thick.

Such chemical apparatus consists of rolled sheet lead and extruded lead pipe assembled as tank linings and conveyances for chemical solutions primarily in the sulphuric acid plant.

In this country the soft-soldered wiped joint is used instead of the welded joint for lead plumbing and cable sheathing, whereas in Europe lead plumbing and roofing commonly are welded. Broken zinc-base die castings are repaired by welding, and wrought zinc sheet has been torch and spot welded, although there have been few applications, such as rain gutters. A comprehensive book on lead welding has been written by Partington.‡ The thickness of lead customarily is designated as pounds per square foot (1 lb. lead is $^1/_{64}$ in. thick, 4 lb. lead is $^4/_{64}$ in. thick, etc.)

In lead welding there are occasions upon which an exhaust ventilator may be used to advantage to remove fumes of lead or lead compounds. Lead dust from shaving and filing operations may cause poisoning unless precautions are taken to avoid inhalation.

Welding Lead with the Torch

The equipment required for lead welding consists of a fuel supply, torch, shaving tools, filler rod ("burning bar"), and molds for heavy vertical welds. Several fuels may be used: oxy-hydrogen, oxyacetylene, air-hydrogen, air-acetylene, oxy-city gas, etc. Compared with torches for welding steel, the operator uses diminutive torches even when welding the thickest lead. The tips supply $^1/_2$ to 5 cu. ft. per hr. of oxygen depending on the thickness of the lead. The small torches are related to the low specific heat and melting point of lead. Only about 5% as much heat is required to melt lead as to melt the same amount of steel. Furthermore,

* Prepared by a committee consisting of W. Spraragen, Welding Research Committee, *Chairman;* A. C. Hamstead, Carbide and Carbon Chemicals Corp.; G. O. Hiers, National Lead Company.

† "Lead Burning" is a somewhat misleading expression because in the fusion welding of lead, oxidation or burning by oxidation is to be avoided.

‡ PARTINGTON, E. B., *Chemical Plumbing, Lead Burning, and Oxy-Acetylene Welding*, British Oxygen Company, London, 445 pp. (1932).

lead conducts heat only one-half as rapidly as steel. As a result, lead melts rapidly under the flame, little heat being lost from the weld puddle to surrounding solid lead.

Besides using a relatively tiny, low-pressure ($1^1/_2$–5 psi.) flame $1^1/_2$ to 3 in. long, the lead welder adjusts the flame to neutral. A reducing oxyacetylene flame may deposit soot on the scarves, whereas an oxidizing flame oxidizes the lead and prevents welding. Lead oxidizes upon exposure to air or oxygen even at room temperature. The lead oxide is a little lighter than lead (specific gravities are 9.4 for lead oxide, 11.3 for lead) and melts at a higher temperature, 850°C. compared with 327°C. for lead. If a sound weld is to be secured, the edges and surfaces to be welded as well as the surface of the filler rod must be shaved bright with a shaving tool immediately before welding. The shaving tool has a sharp edge and is used to scrape the dark oxide from the filler rod and scarves. Shaving is imperative for all types of welds because no flux is used.

Two types of flame are used: (1) A pointed flame to secure fusion at the bottom of lap or butt joints, or to hold the molten metal in place in overhead welding. The gas pressure is raised to obtain a pointed flame. (2) A blunt flame characteristic of low gas pressure for a given tip. The blunt flame is used to deposit all but the root layer in multi-layer joints.

The filler rod should have the same composition as the lead or lead alloy to be welded. The filler rod is a little thicker than the lead to be welded; for example, a bar $^1/_4$ in. in diameter is used to weld lead sheets $^1/_8$ in. thick. If the bar is too thin, oxidation may occur; if too thick the weld puddle is chilled.

The technique of lead welding depends on the position. Lap and butt welds in the flat position are made with filler rod. In the vertical position lap welds without filler rod are used for sheets up to about $^1/_4$ in. thick; thicker plates are butt welded with filler rod and an iron mold. Lap welding without filler rod always is used for overhead welds, while horizontal welds in vertical plates always are lap welded with or without filler rod.

Flat Welding.—The manipulation of torch and rod in butt welding lead in the flat position is different from the technique for steel or aluminum. The shaved edges to be joined are fused with the torch before the filler rod is placed in the flame. After the drop from the filler rod is added to build up the weld, the filler rod is withdrawn, while the torch is moved ahead to melt another section of the edges. When these edges have melted, another drop from the filler rod is added, the rod being melted in the reducing zone of the flame. The drops overlap to form a herringbone pattern. Any attempt to form a large molten puddle is likely to result in melting a hole or losing the molten metal through the gap between the edges. Although the dropping procedure is customary for butt welding lead, it is possible to weld lead pipe like steel pipe by maintaining the rod in the puddle at all times.

For sheet lead up to $^1/_{16}$-in. thick flanged joints are used. The upturned flanges are melted together with the torch without rod. Thicker lead up to $^1/_6$ or $^1/_4$ in. thick is butted together without beveling. The joint is tacked every foot, and the fit should be fairly good, otherwise time will be lost in the difficult operation of filling a wide gap. Plates over $^1/_4$ in. are beveled, the included angle being 50 to 90°. Five to ten layers may be

required for a beveled butt joint in lead $^3/_8$ in. thick. Backing strips or reverse beads are not used.

Lap joints are simpler to weld than butt, one plate being joggled to produce a flush appearance on one side. The lap joint may or may not be more flexible than the butt joint, but always requires more metal. The overlap generally is $^1/_2$ to 2 in., depending on thickness. Welding proceeds by moving the torch in a semi-circular path toward the overlap, then straight away. The upper plate is melted over a width of $^1/_4$ in., the lower one $^3/_8$ in. for $^1/_8$-in. sheet. Five layers may be required for lap welds in $^1/_2$-in. plate.

Vertical Welding.—Lap welding without filler rod is applicable for welding vertical sheets up to $^1/_4$ in. thick. The overlap is 1 to 3 in. and the edge of the overlapping sheet may be bent outward slightly to serve as filler metal and to give a rounded finish to the joint. The seam is started at the bottom, the first drop being supported by an iron rod, if the lower end of the weld does not rest on another lead plate. The tip of the flame bisects the angle between the edge of the near plate and the surface of the far plate. With a circular motion the operator melts the far lap, then melts a small amount of the near lap into the molten far lap. The torch is moved higher to repeat the process while the lower bead freezes. In this way the weld is carried to the top as a succession of flat discs of weld metal.

An iron mold is required to make butt welds joining plates over about $^1/_4$ in. thick. The mold is 5 to 6 in. long and is semi-cylindrical, the diameter being $^1/_8$-in. wider than the width between the beveled scarves. The torch fuses the scarves surrounded by the mold as filler rod is added. When the mold is filled, the torch is withdrawn. The lead freezes and the mold is raised for the next increment of joint.

Overhead Welding.—The sheets in overhead welding are overlapped and a tiny pointed, intense flame is used to melt the edge without filler rod. The melted lead is held in place by capillarity and by the force of the flame. The molten metal from the fused edge is caused to merge with molten metal on the surface of the far lap, as the torch is moved from edge to far lap.

The speed of butt welding in the flat position is not greatly different from the speed for torch welding steel. Speeds of $1^1/_3$ ft. per min. are attainable with 6 lb. sheet lead. Vertical welding and particularly overhead welding are slower than flat welding. The criteria of good welds are:

(*a*) Full penetration at root, without drip.
(*b*) Absence of undercut.
(*c*) Uniform width and reinforcement.
(*d*) Uniform herringbone pattern.

Lead Pipes and Lead Linings

The type of joint for pipes depends on the position and size of the pipe. Cup or bell joints (overlap = 3 T or more) are simple for vertical pipes, whereas butt joints are most economical for any joint that can be rolled horizontally during welding. The split or flap joint is peculiar to lead piping and is adopted to avoid overhead welding in position. The bottom of the joint is welded from the inside of the pipe by cutting flaps in the up-

per part and bending them open, after which the flaps are folded back and welded in place, so that all of the welding is applied in the flat position.

To line steel or wood tanks with lead sheets it is customary to screw, bolt or rivet the lead to the tank, to weld lead protectors over the bolts and to weld the joints between the sheets. Instead of steel bolts and rivets, lead rivets may be used. The sheets are welded to the lead rivets, no protectors being required. Homogeneous lead linings on steel and cast iron are produced by fusing the lead on the fluxed steel with or without an intermediate layer of tin or solder. If no tin is used, the steel must be pickled and heated with zinc chloride or other flux before the lead is deposited. Pinholes and cracks in the lining are fatal to the success of such a lining.

Metallurgy.—Oxidation is the main metallurgical phenomenon in lead welding. Oxide on the scarves interferes with penetration, while an oxidizing flame coats the drops on the rod with lead oxide and prevents their merging with molten base metal. Oxide in the weld lowers the corrosion resistance. No practical flux for the oxide has been found.

Weld metal in unalloyed lead is coarse grained, which favors resistance to creep. If some alloying elements, such as 0.06% Cu., are present, the weld metal may be fine grained. Peening improves the properties of the lead weld metal.

Soldering.—Lead pipes and cable sheaths frequently are joined by the wiping process. Solder containing 70 Pb., 30 Sn. is melted and poured around the joint. Tallow is used as flux to protect the surfaces from oxidation. In contact with the cold pipe or sheath the solder cools to the mushy condition, in which it is a mixture of tin-rich liquid metal and solid crystals of lead. The mushy mixture is molded like putty around the joint. The disadvantages of the wiping process are the relatively expensive tin-lead solder which is required in large quantities, and the time-consuming preparation demanded by the joint. Soldering replaces welding generally only when corrosion resistance is not a significant factor.

WELDING WROUGHT ZINC WITH THE TORCH

Unlike lead, flux is used for welding wrought zinc and its alloys. Besides preventing oxidation of zinc by means of flux, the operator also is careful not to heat zinc far beyond its melting point during welding, for zinc boils at 905°C., only 500°C. above the melting point, and evaporates rapidly above 600° or 700°C. The zinc evaporates from the weld puddle as hot metal gas and combines with the air to form a fume of solid zinc oxide above the weld. If flux covers the weld puddle, both evaporation and oxidation are prevented to a great extent. Zinc cannot be shaved so readily as lead, and in any event the oxide forms on a shaved zinc surface at once.

The principal requirement for torch welding is flux, which may be a half-and-half paste of zinc chloride and ammonium chloride (salammoniac). The oxide film on zinc alloys containing 4% aluminum is difficult to flux. Flux is applied on both edges of the sheet and on the filler rod, which should deposit metal of the same composition as base metal. A small oxyacetylene torch is used. Unlike the oxidizing flame for brass welding, the flame for zinc is neutral or slightly reducing. A torch suitable for steel $^1/_{32}$ in.

Appendix—Properties of Lead and Zinc

Metal or Alloy	Chemical Lead	Tellurium Lead	Antimonial Lead	Zinc	Zinc Aluminum Alloy	Zinc Ternary Alloy
Lead	99.92%	99.87%	94%	1.6% max.	0.007% max.	0.007% max.
Tellurium	....	0.05%	....	....	....	....
Copper	0.06%	0.06%	....	....	0.10% max.	3%
Zinc	None	None	None	Remainder	Remainder	Remainder
Aluminum	None	None	None	....	4%	4%
Magnesium	None	None	None	....	0.05%	0.05%
Antimony	None	None	6%	....	....	....
Melting point, liquidus	326°C.	326°C.	285°C.	419°C.	381°C.	379°C.
Melting point, solidus	326°C.	326°C.	247°C.	....	....	....
Specific gravity	11.3	11.3	10.9	7.1	6.6	6.7
Thermal coefficient of expansion per °C. $\times 10^6$ at 20°C.	29.5	29.5	27	23–32.4	27.4	27.7
Thermal conductivity, cal./cm.^{2}/cm./°C./sec.	0.083	0.083	0.069	0.27	0.27	0.25
Electrical resistivity, mass	12.3 × copper	12.3 × copper	14 × copper	3.5 × copper	3.8 × copper	4.1 × copper
Total heat in liquid at melting temperature in Btu. per lb.	28	28	30	117	118	120
Tensile strength, cast psi.	2600	3000	6800	5400	40,300	48,000
Elongation, cast in %	50	45	24	0	3	3
Tensile strength, rolled psi.	2400	3000	4500	20,000	....	....
Elongation, rolled in %	50	40	50	40	....	....
Endurance limit at 10^7 cycles in psi.	600	900	1100	....	....	....
Maximum allowable fiber stress at 20°C. in psi.	200	200	400	....	....	....
Maximum allowable fiber stress at 100°C. in psi.	127	127	165	....	....	....
Maximum allowable fiber stress at 120°C. in psi.	110	110	110	....	....	....
Maximum allowable fiber stress at 150°C. in psi.	80	80	...	....	....	....

thick is suitable for zinc $^1/_8$ in. thick. The joint is prepared in about the same way as for steel. Thin sheets $^1/_{32}$ in. thick are flange welded without filler rod. Unbeveled butt welds are made up to $^1/_8$ in. thick. Thicker zinc is beveled to form 70–90° grooves. Tacking at intervals of about 4–6 in. is helpful. Long seams sometimes are lap welded to save time in fitting the edges.

The welding procedure resembles that for aluminum, in that holes are formed if the torch is held vertically. Therefore, the torch is held at an angle of 15° to 45° to the sheets. On the other hand, in welding zinc the flame is directed on the rod which is raised out of the flame for an instant after each drop has been deposited. It seems to be immaterial whether the flame is pointed toward or away from the deposit. The rod may be used to stir the puddle and coalesce the molten metal, while the torch is given an oscillating motion to avoid dwelling too long on one spot and melting a hole. Sheets $^1/_8$ in. thick have been butt welded at the rate of 25 ft per hr.

Vertical butt or lap welds are started at the bottom. Either the torch is applied periodically to form a succession of drops, or the torch is held nearly parallel to the sheets to melt the seam continuously.

Peening the weld at 100–150°C., refines the grain size and may improve the mechanical properties. Peening at room temperature or above 150°C. may crack the weld.

Spot and seam welding have been used to fabricate wrought zinc parts.

WELDING ZINC-BASE DIE CASTINGS

Broken zinc-base die castings as thin as $^1/_{32}$ in. have been oxyacetylene welded successfully by a number of experts, provided the castings have not been oxidized. Welding is difficult and is confined to repair work. The edges to be welded may be filed or may be scraped to a V with a steel spatula after being heated to the sweating point. The filler rod may be pure zinc or, better, a die-casting alloy of the same type as that to be welded. Flux is used by some authorities (50% $ZnCl_2$, 50% NH_4Cl), but most operators use none because alumina* cannot be fluxed at welding temperatures, 350–420°C. The majority prefer a reducing flame, but no soot should be deposited. The flame should be directed on the filler rod to prevent overheating the casting. It appears, therefore, better to direct the flame nearly parallel to the surface rather than nearly vertical. Plaster of Paris is used sometimes to support the casting during welding, while a graphite mold may be used to prevent liquid weld metal flowing away while the weld is being stirred.

* Aluminum oxide, a non-metallic substance

CHAPTER 26

CLAD STEELS*

Definition, Kinds of Clad Steels, Uses, Methods of Manufacture, Clad Metals Available, Fabrication, Welding Electrodes, Precautions, Code Regulations.

1. Definition

A CLAD steel plate is a composite plate made up of a commercial grade steel plate, to one side or both sides of which there is uniformly and permanently joined a veneer or cladding of a corrosion and/or heat-resisting metal, the thickness of which is a substantial proportion of the total plate thickness.

2. Kinds of Clad Steels

The clad steels available are nickel clad, Monel clad, Inconel clad, silver clad, copper clad, cupro-nickel clad and stainless clad. The stainless clad types commercially available are those clad with grades 304, 310, 316, 317, 347, 405, 410, 430 and 446 of stainless steel.

The available compositions of cladding may be furnished with variable specifications of steel backing plate, that is, flange quality, firebox quality, commercial low-alloy steels, in A.S.M.E. grades S-1, S-55, etc.

3. Uses

Clad steels are used to provide corrosion and/or heat-resisting surfaces for protection of substances in contact therewith more economically than similar pieces of solid material. Clad steels are used in equipment in the petroleum, brewery, bakery, dairy, paper and pulp mill, food processing, textile mill, transportation, chemical and other industries.

4. Methods of Manufacture

(*A*) *Heat and Pressure Method* (*Fig. 1A*)

The process used in the making of clad steel employing heat and pressure produces a bond between the cladding and the steel to form a highly effi-

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* Prepared by a committee consisting of W. G. Theisinger, Lukens Steel Company, *Chairman;* H. S. Blumberg, The M. W. Kellogg Company; O. R. Carpenter, Babcock & Wilcox Company; J. J. Chyle, A. O. Smith Corporation; A. R. Eckberg, Eastman Kodak Company; T. S. Fitch, Jessop Steel Company; F. G. Flocke, The International Nickel Company; R. A. Lincoln, Allegheny Ludlum Steel Corporation; H. P. Owen, Ingersoll Steel & Disc Div., Borg-Warner Corp.; S. K. Varnes, E. I. DuPont de Nemours & Company.

cient union of the two metals. A heavy slab of steel, selected for its physical properties in accordance with the design specifications, is blasted and thoroughly cleaned on one of its flat surfaces. A plate of the material to serve as cladding with one surface blasted or otherwise specially prepared, is placed on the steel slab and held in place by welds and bars. A second similarly prepared slab of steel and plate of cladding material is placed upon the first one with the clad surfaces facing, with an infusible compound between them. This makes a four-layer slab or "sandwich."

This sandwich, held together and sealed by welding, is heated in the steel mill soaking pits to a temperature of 2250 to 2300°F., and rolled in a mill under great pressure. This pressure on the white hot composite assembly reduces its thickness and thus plastically bonds the cladding and the steel together.

The edges of the rolled composite assembly are sheared and the two component parts of the sandwich are separated, yielding two plates of clad steel, whose clad surfaces have been uncontaminated by the heating flame or gases, the hot working operation or any of the mill appliances.

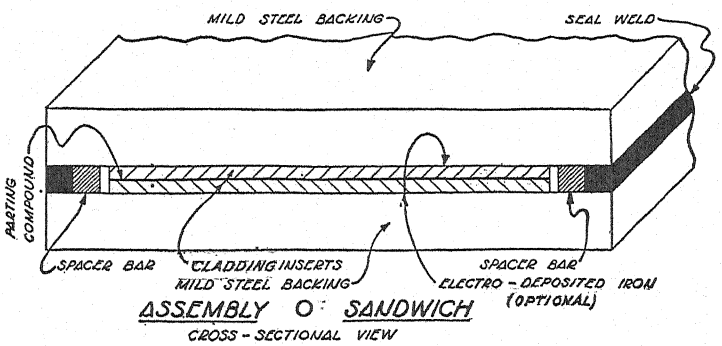


Fig. 1A

(*B*) *Casting Method* (*Fig. 1B*)

A stainless clad type is made by casting mild steel around an assembly of stainless steel plates separated by insulating material and edge welded. The composite assembly is then rolled as in the heat and pressure method, and separated into two plates of clad steel after shearing the four edges.

(*C*) *Spot or Resistance Welding* (*Fig. 1C*)

As the name implies a sheet of alloy metal is bonded to relatively thicker plate by spot welding. This backing plate may be mild steel of flange or firebox quality, or other commercial low alloy steels in A.S.M.E. grades S-1, S-55, etc.

The base plate which is to serve the cladding is prepared by surface blasting one side to be bonded. The distance between the centers of the spot welds may vary from $^3/_4$ in. to 3 in. or more.

(*D*) *Stream Welding* (*Fig. 1D*)

In this process a sheet of cladding steel is also spot-welded to a relatively

thick mild steel plate, except that the spot welds are made to overlap one another, to produce in effect a stream of spot welds. The adjoining "streams" may or may not overlap and thus the product may be an integrally clad plate in one case and an intermittently welded clad plate in another. In some cases a plurality of sheets is attached likewise to the mild steel plate.

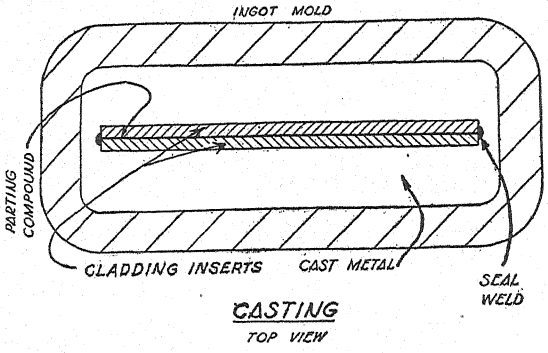


Fig. 1B

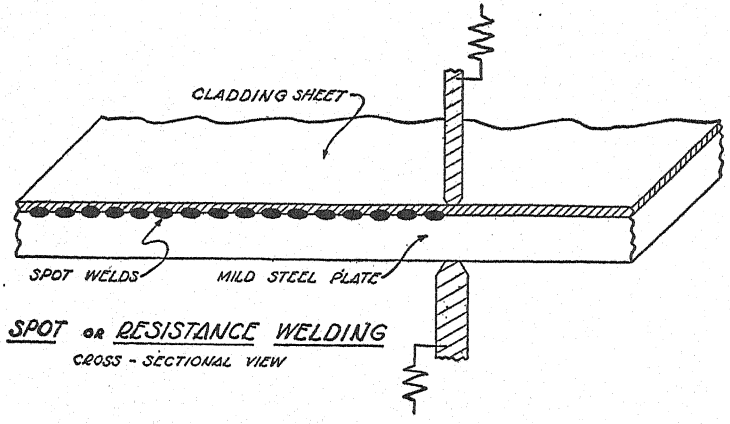


Fig. 1C

(*E*) *Intermelting* (*Fig. 1E*)

In this process a refractory wall forms three sides of a mold and the steel backing ingot provides the fourth side. In this jacketed space the alloying ingredients are introduced and intermelted with the surface of the steel ingot by an electric furnace operation, to produce an alloy facing of controlled and uniform composition. The result is an integrally bonded composite material which is heated and rolled to gage by the mill in the usual manner.

(*F*) *Fusion Melting* (*Fig. 1F*)

A mixture of ferroalloys, nickel, iron and suitable slag, all in granular form, is placed on the face of a steel slab. An arc is moved along the face

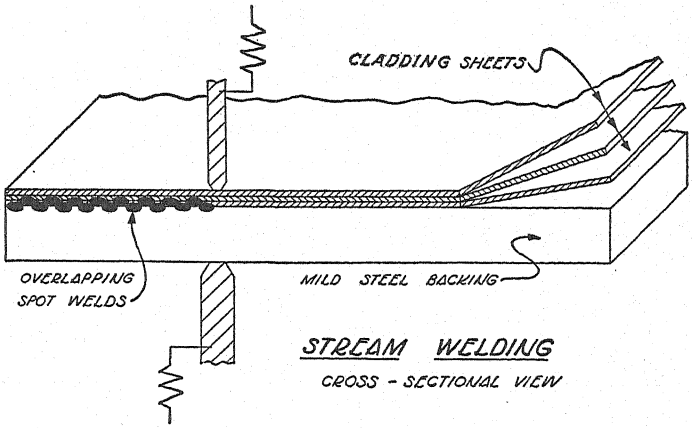

CLADDING SHEETS
OVERLAPPING SPOT WELDS
MILD STEEL BACKING
STREAM WELDING
CROSS - SECTIONAL VIEW

Fig. 1D

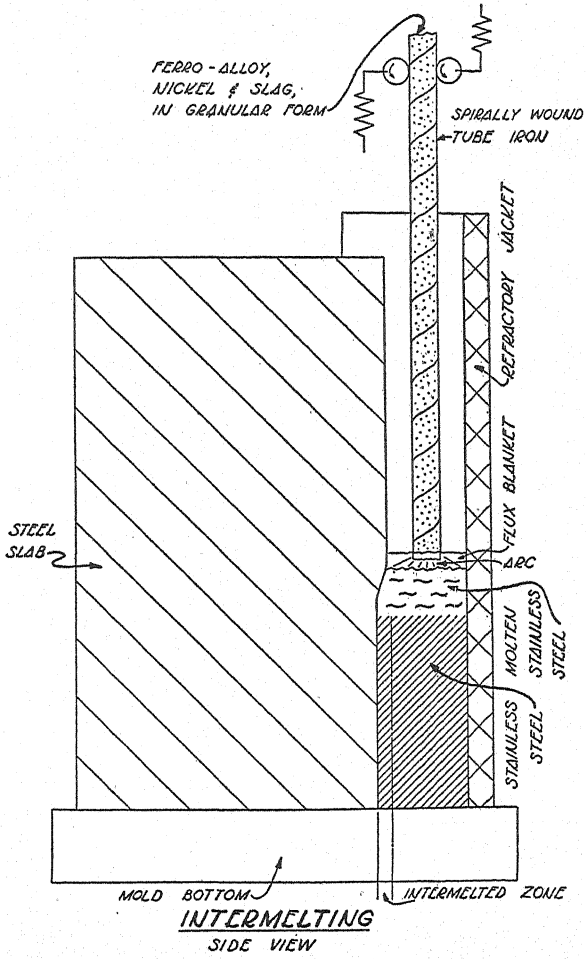

FERRO - ALLOY, NICKEL & SLAG, IN GRANULAR FORM
SPIRALLY WOUND TUBE IRON
REFRACTORY JACKET
FLUX BLANKET
ARC
MOLTEN STAINLESS STEEL
STAINLESS STEEL
STEEL SLAB
MOLD BOTTOM
INTERMELTED ZONE
INTERMELTING
SIDE VIEW

Fig. 1E

causing an interfusing of the cladding and the base metals. The resultant composite slab is then heated and rolled in the usual manner.

(G) *Arc Welding (Fig. 1G)*

Overlapping beads of weld metal may be deposited by electric-arc, oxy-acetylene or atomic-hydrogen welding onto one face of a mild steel slab. The resultant clad slab may then be ground, heated and rolled in the customary manner.

The manufacture of three-ply, or double-clad plate may be accomplished by several of the above methods with self-evident modifications.

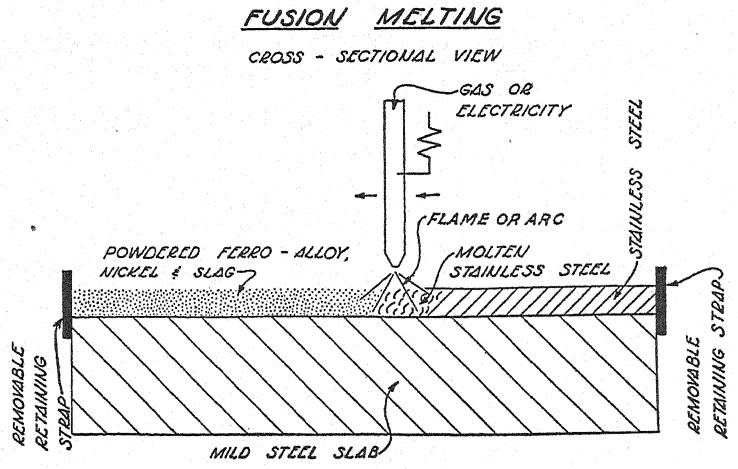


Fig. 1F

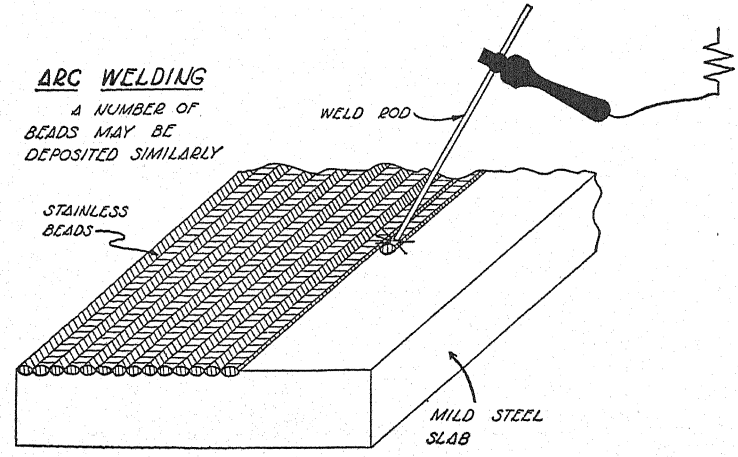


Fig. 1G

5. Clad Metals Available

Nickel-clad, Monel-clad, Inconel-clad, cupro-nickel clad, copper-clad, silver-clad and stainless-clad steels are available in the form of sheared flat

plates and sheets in essentially the same sizes and gages as commercial rolled steel. Pressure vessel heads, flanged, flanged and dished, elliptical, hemispherical and conical are available.

The clad steels are usually furnished with the cladding on one side of the composite plate. However, for partitions in vessels and other uses where the contents may be in contact with both sides, the two flat surfaces may be clad, forming double-clad or 3-ply clad steel.

The thickness of the cladding itself may vary from 5 to 50% of the total composite plate thickness, or it may be a constant thickness as 0.031 in., etc., regardless of the steel backing plate thickness.

6. Fabrication

(*A*) *Forming*

(*1*) *Cold.*—Cold operations such as bending, rolling, flanging, forming, shearing, beveling and the like are performed exactly as in common steel fabrication. No change in equipment or provision for special tools is necessary.

(*2*) *Hot.*—Clad steel is hot formed with about the same facility and with the same equipment as mild steel, provided proper means for heating are available. A fuel with 0.5% maximum sulphur (preferably less) is required in heating clad steel.

The nickel-, Monel- and Inconel-clad steels should be heated outside the combustion zone, in a reducing atmosphere. Heavy duty heating torches—either oxyacetylene or oil—are satisfactory.

The austenitic stainless steels should be heated in a neutral atmosphere or be protected with a cover plate of mild steel.

It is advisable to protect clad surfaces so that die marks, gouges and the like do not mark the surface to an extent requiring repairing. Some of the straight chromium alloys are air hardening and, should a substantially soft alloy face be required, the hot-worked composite materials of this class will require a subsequent heat treatment.

(*B*) *Preparation for Welding*

(*1*) *Shearing.*—Clad steel can be sheared with the same equipment used for steel. In handling clad plate horizontally to and from shears, punches and planers, clad surfaces should be placed to face upward to avoid gouging or deeply scratching the cladding. Whenever practical, shearing should be done with the clad surfaces up.

(*2*) *Flame Cutting.*—In general, it is preferable to chip off the cladding to the steel along the line of cut and flame cut through from the clad side.

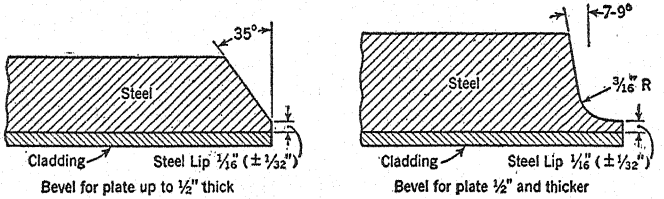


Fig. 2—Clad Plate Edge Preparation for Welding

Thick plates in gages $^5/_8$ in. and heavier are flame cut from the steel side with the torch head inclined about 10°, with the tip pointing toward the completed cut. A tip one size larger than for steel should be used with increased oxygen pressure.

(*3*) *Edge Preparation for Welding.*—Butt Joints, Fig. 2. Grooves may be flame cut, chipped or planed as in steel plates.

Lap Joint. Square edges—machined or square sheared.

Fillet Joint. Follow same practice as in steel for similar conditions.

(*C*) *Welding Processes*

(*1*) *Metal Arc.*—Arc welding is generally employed for joining clad steel except in less than 18 gauge. (See Fig. 3.) The steel side of the clad metal

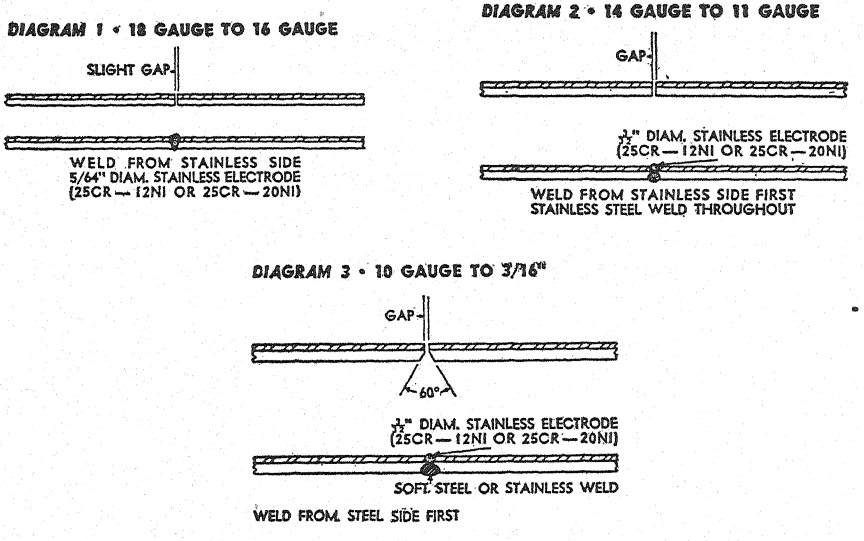


Fig. 3

should be welded with a steel electrode and the clad side with a welding electrode of the appropriate metal. Tack welding during assembly of joints is always done on the steel side with steel electrodes.

(*2*) *Gas Welding.*—This method is seldom used for fabricating lined or clad metal of heavy gages.

(*3*) *Resistance Welding.*—This method has no application in fabricating heavy gage clad composite plates.

(*4*) *Atomic Hydrogen Welding.*—This process is commonly used for joining silver clad and light gage clad metals.

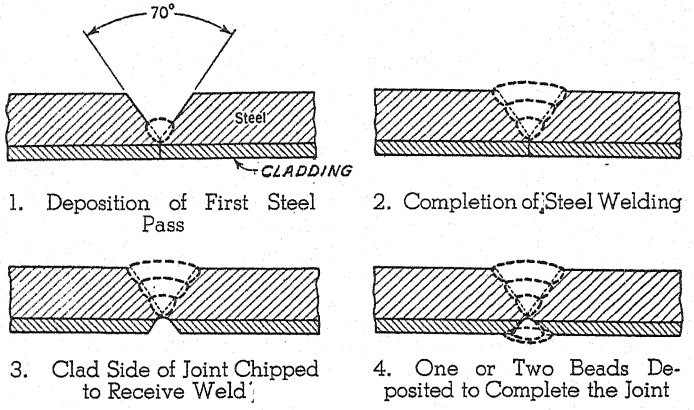
(*D*) *Welding Procedures*

(*1*) *Butt Welds.*—(*a*) Light Gages. In butt welding the lighter gages of clad sheets no preparation of the edges is necessary other than to observe proper shearing methods, as outlined in Section 6(*B*). (See Fig. 3.)

Wherever possible, there should be a slight spacing between the sheet edges to be welded. In the lower ranges of these light gages—about 18 gage to 16 gage, the electrodes should be carefully chosen and the welding done from the cladding side in one pass. See Fig. 3, Diagram 1. From about 14 gage to 11 gage, the weld may be made in two passes, the first to be made from the clad side and the second from the steel side. Here a $^3/_{32}$-in. diameter electrode is recommended. The weld from the steel side may also be made with covered steel electrodes of the same diameter. See Fig. 3, Diagram 2.

(*b*) Intermediate Gages. In welding the intermediate gages from about 10 gage to $^3/_{16}$-in. thick plate beveling of the edge on the steel side is usually recommended. However, if the operator wishes, he may butt weld clad sheets in this thickness range without beveling the edges, following the procedures outlined in the preceding paragraph. In this case, the clad side should be welded first. Where it is more desirable or economical to make a composite weld in this thickness range, the steel side should be beveled as shown in Fig. 3, Diagram 3. Note that the point of bevel remains in the steel layer slightly above the cladding. The steel side should be welded first with a covered steel electrode.

Following this steel weld deposit, the slag must be thoroughly removed from the clad side of the weld groove before attempting to weld the clad side. This weld should be made in a single pass with a $^3/_{32}$-in. diameter welding electrode.



1. Deposition of First Steel Pass
2. Completion of Steel Welding
3. Clad Side of Joint Chipped to Receive Weld
4. One or Two Beads Deposited to Complete the Joint

Fig. 4

(*c*) Heavy Gages. Clad steel in thicknesses heavier than $^3/_{16}$ in. is often used to withstand pressure which requires welds having maximum strength and ductility, as well as corrosion resistance. The most commonly used procedure in arc welding clad plate, particularly with beveled butt joints, is to weld the steel side first (this prevents the possibility of forming a hardened area), then the clad side (see Fig. 4), as follows:

1. Assemble the vessel by tacking from the steel side, with steel welding electrodes.
2. Complete the weld on the steel side with steel electrodes.

3. Chip out the clad side of the butt joint down to clean, sound steel weld metal, using a $^{3}/_{16}$-in. or $^{1}/_{4}$-in. round nose gouge so as to leave a clean groove, with good contour for welding.

4. Fill the chipped groove with two or more layers of welding, using electrodes of size and type appropriate for the clad side.

5. Where the full corrosion resistance of the cladding material is required in the weld zone, the welding electrode should be of such a composition as to allow for the normal dilution occurring in the welding process. For example, in Type 304 stainless clad welding, "25-20" electrodes are recommended. See Section 7 "Welding Electrodes" for further recommendations on the selection of welding rods.

For some installations, an alternative method of welding the clad side first can be used if the steel plate edges are machine beveled and if the butt joint can be assembled with the lips in tight contact and in close alignment. The procedure followed is (*a*) to tack weld from the steel side, (*b*) weld the clad side, which should not be beveled, with the appropriate size electrode and (*c*) upon completion of the welding of the cladding steel tacks should be chipped out and the steel side welded. To avoid excessive penetration of the cladding during steel welding, care must be taken to use no larger than a $^{5}/_{32}$-in. diameter steel electrode for the first steel pass. Any convenient diameter steel electrode can be used for subsequent steel passes.

For the steel welding, any good covered electrode suitable for tank or pressure vessel welding may be used. The accustomed practices prevailing in the shop, including manual and automatic types of equipment, size and type of welding rod, current adjustment and manipulation peculiar to individual operators, are used without important modifications in welding the steel side of the clad steel.

The skilled operator should have no difficulty in welding the cladding. Operators inexperienced in the welding of clad steel should study the instructions distributed by the welding rod or clad metal manufacturers and then should make a few welds on scrap clad steel to become accustomed to the flow of the cladding weld metal. The principal points to be observed in the preparation of the joints, assembly and welding are:

1. The edges of the clad metal should be cut to give uniform alignment at the joint.

2. Beveled butt joints should be assembled as shown in Fig. 3, with the edges of the bevel at the lip butted tightly.

3. On joints welded first from the steel side, the clad side should be cleaned free from "icicles," slag and heavy oxide. It is advisable to chip the seam with a round nose chisel to a depth necessary to expose sound metal at the root of the steel weld.

On joints welded first from the clad side, the tack welds should be chipped out on the steel side and the root of the bevel chipped to clean sound metal.

4. The operator should make trial welds at several settings in the ranges given by the electrode manufacturer and select the setting that best suits the nature of the work and his own manipulative methods.

(*2*) *Fillet Welds.*—Figure 5 shows typical inside and outside fillet welds on clad steel plate. In making fillet welds, it is advisable to make the welds on the steel side first, following with the welds on the clad side.

(*3*) *Seal and Lap Welds.*—Whenever it is necessary to weld the steel layer to clad steel as in the case of lap welds, or to seal the edges of the clad sheets or plates, the welds in contact with the mild steel should be made with the same electrode used on the clad side.

(4) *Typical Connections and Openings (Fig. 6).*

(E) *Finishing and Cleaning*

Upon completion of fabrication of any clad steel equipment involving welded fabrication, it is essential to clean the weld and weld area to prevent corrosion; in the case of stainless types it is advisable to passivate the entire clad surface to remove dirt, grease or iron particles that may have been imbedded in the clad surface during fabrication.

(1) *Removal of Flux.*—The first cleaning operation is for the purpose of removing the slag and flux in the weld area. These may be removed mechanically by sand blasting, motor-driven rotary wire brush or by acid pickling. Some fabricators prefer a combination of acid cleaning and wire brushing.

(2) *Grinding.*—Some clad steel fabrication requires that the welds be ground flush particularly in those types of process equipment where slight

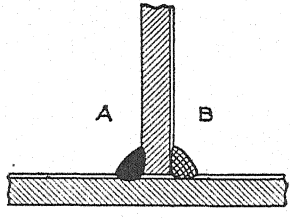


Fig. 5—Fillet Welds

Weld A should be made with an electrode appropriate for joining dissimilar metals, such as a Monel electrode joining nickel to steel.

Weld B should be made with an electrode of the same general composition as the cladding.

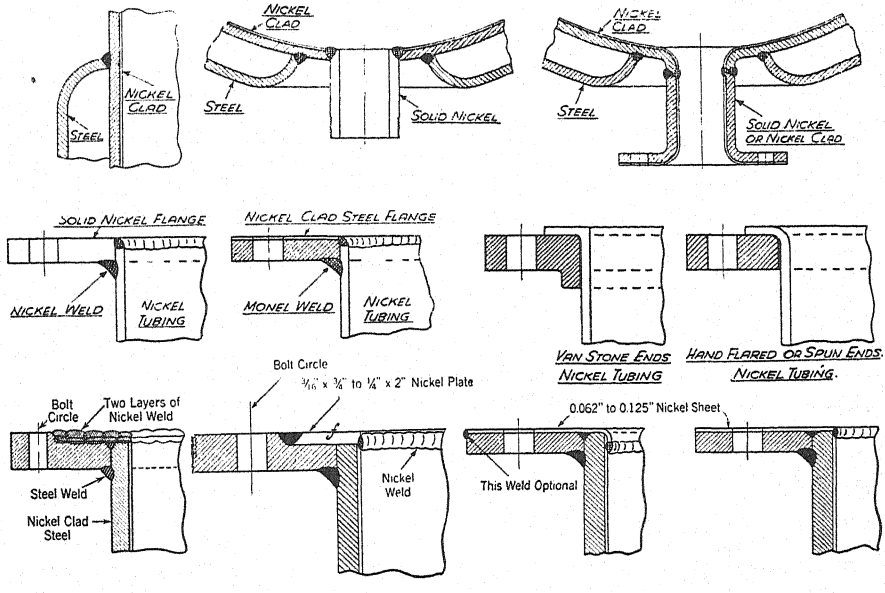


Fig. 6—Above Is Illustrative Only with Nickel Clad as an Example. Other Clad Steels May Be Assembled in Like Manner by Procedures and Selection of Materials as Recommended by the Manufacturer

crevices and irregularities might cause contamination. If reasonable care is used there need be no hesitation in grinding clad steel butt welds where the cladding has a minimum thickness of approximately 0.030 in.

Grinding wheels should be a free cutting type such as rubber or bakelite bonded wheels and used at the speeds recommended by the manufacturers. For normal weld grinding a No. 36 grit wheel may be used, either straight or cone type, whereas, rough cuts may be done with a 16 grit wheel.

Where the ground welds require subsequent polishing, a 60 or finer grit wheel may be used for the final grind. The resulting scratches will be shallow and readily removed in the polishing operations. Grinding wheels that have been used on metals other than that to be ground should not be used on clad surfaces without thoroughly dressing the wheel first to remove all inclusions that might otherwise become imbedded in the clad surface.

(*3*) *Cleaning or Passivation Methods.*—After the weld and weld area have been cleaned of slag it is advisable to clean or passivate the entire clad surface of stainless clad vessels using 10 to 50%, by volume, cold nitric acid.

(*4*) *Polishing.*—Specific recommendations should be obtained from the supplier of the clad metals. Polishing wheels used on the clad surface should not be used on any other metals.

(*F*) *Heat Treatment*

Nickel-clad, Monel-clad and Inconel-clad steels require no heat treatment after fabrication and before being placed into service, except in the case of pressure vessels requiring stress relief. The same time and temperature treatment applied to carbon steels is used for these clad steels, namely: heating to a temperature between 1150° and 1200°F. and holding for one hour for each inch of material thickness and cooling slowly in the furnace. For straight chrome-clad steels and the austenitic chrome nickel-clad steels, the above heat treatment may not apply and the definite treatment required depends upon the type of alloy used as a cladding for the composite plate. The recommendations of the manufacturer of the clad material should be followed. In general, the straight chrome stainless clad steels should be heated within the range of 1200° to 1450°F., and cooled in the furnace. Stress relieving of 18–8 steels may be done at a temperature between 1150° and 1250°F. followed by furnace cooling, but carbide precipitation may result in a reduction in corrosion resistance. For many types of service this may be satisfactory. However, where it is suspected that carbide precipitation would result in intergranular corrosion, columbium bearing steels should be used. The best heat treatment for 18–8 is a rapid cool from 1950°F. but this cannot be done in most cases, because of distortion and other factors.

General

In vessels made up of parts of unequal thickness, such as tube headers welded to shell plates, it is especially important to heat very slowly to the stress-relieving temperature so that all sections are maintained at the same temperature. Unequal heating of varying thicknesses welded together

may be more serious than unequal cooling—although both changes should be as uniform as possible.

7. Welding Electrodes

(*A*) *Alloy Content*

On clad steel plates, the steel side is welded with a quality steel electrode and the clad side of a joint is welded with the following electrodes:

On nickel-clad steel plate—a pure nickel welding electrode or an 80 Ni-20 Cr electrode

On Monel-clad steel plate—a Monel welding electrode

On Inconel-clad steel plate—an Inconel welding electrode

On straight chrome-clad materials—a 25–20 Cr-Ni electrode

On 18–8 Cr-Ni—a 19–9 Cr-Ni electrode or a 25–12 Cr-Ni electrode or a 25–20 Cr-Ni electrode

On 18–8 (type 347)—a columbium bearing electrode, 18–8, 25–12 or 25–20

The composition of the stainless welding electrodes is usually higher in alloy content than the base metal. The excess compensates for dilution of the deposited metal from the electrode with small amounts of the iron from the steel base. Therefore, the corrosion resistance of the weld is essentially equal to that of the clad portion of the composite plate. Nickel-clad steel may be welded with a pure nickel electrode on the clad side and the use of two beads of nickel weld metal will reduce the iron dilution at the surface to a small amount. The 80 Ni-20 Cr electrode may be used on nickel-clad steel in which case the iron dilution forms a type of Inconel composition in the weld metal.

(*B*) *Size*

In general, for plates $^{3}/_{16}$ in. and heavier, electrodes $^{1}/_{8}$-in. and $^{5}/_{32}$-in. in diameter are used. Usually a $^{1}/_{8}$-in. diameter electrode is employed in welding the clad side of plate up to about $^{1}/_{2}$ in. thick and, for plate heavier than $^{1}/_{2}$ in., $^{1}/_{8}$-in. electrode is used for the first pass and $^{5}/_{32}$-in. for the succeeding passes.

8. Precautions

In the handling of clad material it is necessary to exercise care, including reasonable precautions consistent with the handling of any quality material. These instructions should be observed:

1. When bending, the rolls should be clean; wrap paper on rolls or protect by pasting paper on the clad surface of the plate.
2. Avoid mechanical abuse such as dropping tools and the like on the clad surface.
3. In forming do not attach temporary fit-up lugs or grips on the clad surface.
4. Avoid striking an arc on the clad surface.
5. During slag removal exercise care in the use of hand tools to avoid mechanical damage to cladding.
6. Protect clad surface from spatter during flame cutting.
7. Avoid use of grinding wheels which may be contaminated.
8. Tools coming in contact with stainless steel should be made of stainless steel.

9. Code Regulations

The A.S.M.E. Boiler Code Committee, April 24, 1936, approved Case 828 permitting the use of nickel-clad steel. This was the first approval by this body of any clad material. The thickness of the backing steel only could be used in design calculations. The latest revision of Case 828 was made September 13, 1940. The case now permits the designer to include the thickness of the nickel cladding as well as that of the steel base plate where the vessel is to operate at not over 100 lb. pressure and/or 250°F. For example a $^1/_2$ in. thick plate of the clad steel made up of 0.400 in. of steel and 0.100 in. of nickel may be calculated for the full 0.500 in. thickness. For pressures greater than 100 lbs. and/or temperatures higher than 250°F. the working pressure is determined by the thickness of the base metal only.

The use of types 410, 430, 446, 304, 310, 316, 317, 321 and 347 integrally stainless clad plate made to specified requirements was approved by the Boiler Code Committee on May 17, 1940. As revised March 21, 1941, the use of such material is permitted for vessels where no corrosion of the cladding is expected with full thickness of the plate allowed in design calculations of working pressure. Where corrosion is expected additional metal thickness must be provided. The reader is referred to the text of Case 896 for full details of the special requirements imposed.

CHAPTER 27A

Tentative Specifications for

IRON AND STEEL ARC-WELDING ELECTRODES[1]

Serial Designation: A 233 – 42 T

ISSUED, 1940; REVISED, 1942.[2]

This is a Tentative Standard and under the Regulations of the Cooperating Societies is subject to annual revision. Suggestions for revision should be addressed to the Headquarters of the A.S.T.M., 260 S. Broad Street, Philadelphia, Pa., or of the A.W.S., 33 W. 39th Street, New York, N. Y.

These specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. (*a*) These specifications cover lightly coated and covered metal arc-welding electrodes for the welding of carbon and low alloy steels of weldable quality.

NOTE.—In connection with the welding of low alloy steels the requirements of these specifications pertain to the tensile strength and elongation of the deposited metal and not to high- or low-temperature characteristics, creep properties, or corrosion resistance.

(*b*) The electrodes are classified on the basis of usability and the ultimate tensile strength of all-weld-metal specimens in the stress-relieved condition, as shown in Table I.

Manufacture

2. The electrodes may be made by any methods that will yield a product conforming to the requirements of these specifications.

Standard Sizes and Lengths

3. Standard sizes and lengths of electrodes are as shown in the following table. In all cases, standard size refers to the diameter of the core wire.

Standard Sizes, Diameter of Core Wire, in.	Standard Lengths, in.
$\frac{1}{16}$	9 or 18[a]
$\frac{3}{32}$	12 or 18[a]
$\frac{1}{8}$ and $\frac{5}{32}$	14
$\frac{3}{16}$	14 or 18
$\frac{7}{32}$, $\frac{1}{4}$, $\frac{5}{16}$, and $\frac{3}{8}$	18

[a] In the case of 18-in. lengths of $\frac{1}{16}$ and $\frac{3}{32}$-in. electrodes, center gripping of the electrodes is standard. In all other cases, end gripping is standard.

Chemical Composition

4. The electrodes shall be capable of depositing metal conforming to the fol-

[1] Under the standardization procedure of the two Societies, these specifications are under the jurisdiction of the A.S.T.M. Committee A-1 on Steel, and of the A.W.S. Filler Metal Specifications Committee.

[2] Revision accepted by A.S.T.M. Committee E-10 on Standards, April 28, 1942; approved by A.W.S. Board of Directors, May 7, 1942.

These specifications which comprise a portion of the former Tentative Specifications for Iron and Steel Filler Metal (Arc-Welding Electrodes and Gas-Welding Rods (A 205 – 37 T)) were published as tentative from 1937 to 1940.

lowing requirement as to chemical composition:

Sulfur, max., per cent.....	0.04

Chemical Analysis

5. The sample for analysis shall be prepared as follows: A specimen of standard base metal (see Section 6 (*a*) and (*b*)) of sufficient size, shall be prepared, and a pad of five superimposed layers of weld metal deposited thereon. The fifth or top layer shall be ground or machined away and discarded. The sample for chemical analysis shall be obtained from the third and fourth layers.

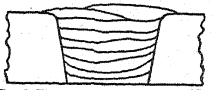
All-Weld-Metal Tension Tests

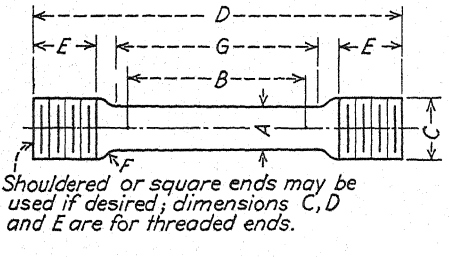
6. Tension tests shall be made as prescribed in the following Paragraphs (*a*) to (*g*):

(*a*) For testing electrodes of the E45, E60, and E70 classifications, the steel to be used for test plates shall conform to either of the following specifications of the American Society for Testing Materials:

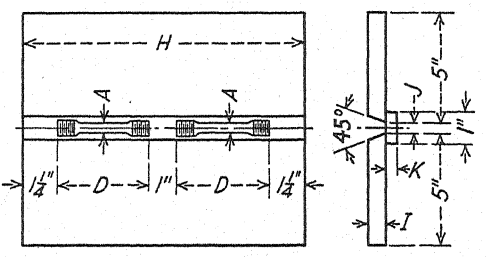
(*1*) Standard Specifications for Carbon-Steel Plates for Stationary Boilers and other Pressure Vessels (A.S.T.M. Designation: A 70).[3]

(*2*) Standard Specifications for Steel for Bridges and Buildings (A.S.T.M. Designation: A 7),[4] open-hearth or electric-furnace steel.

Electrode Size, in.	Test Plate Thickness, in. I	Number of Layers	Diameter of Tension Test Specimen, in. A	Dimensions of Test Plate and Tension Test Specimen, in. B	C	D	E	F	G	H	J	K
1/8	1/2		0.252 ± 0.005	1	3/8	2 1/2	1/2	3/16	1 1/4	8 1/2	1/4	3/16
5/32	3/4		0.500 ± 0.01	2	3/4	4 1/4	3/4	3/8	2 1/4	12	1/2	1/4
3/16	3/4		0.500 ± 0.01	2	3/4	4 1/4	3/4	3/8	2 1/4	12	1/2	1/4
7/32	3/4		0.500 ± 0.01	2	3/4	4 1/4	3/4	3/8	2 1/4	12	1/2	1/4
1/4	1		0.500 ± 0.01	2	3/4	4 1/4	3/4	3/8	2 1/4	12	1/2	1/2
5/16	1 1/4	Each Layer or Pass not to Exceed 1/8 in. in Thickness.	0.500 ± 0.01	2	3/4	4 1/4	3/4	3/8	2 1/4	12	1/2	1/2
3/8	1 1/2		0.500 ± 0.01	2	3/4	4 1/4	3/4	3/8	2 1/4	12	1/2	1/2



Tension Test Specimen.



Test Plate Showing Location of Test Specimens.

FIG. 1.—Requirements for Preparation of Tension Test Specimens.

(*b*) For testing electrodes of the E80, E90, and E100 classifications, the steel to be used for test plates shall conform to one of the following specifications of the American Society for Testing Materials, or shall be a similar steel containing not over 0.30 per cent carbon and having a minimum tensile strength of 75,000 psi.

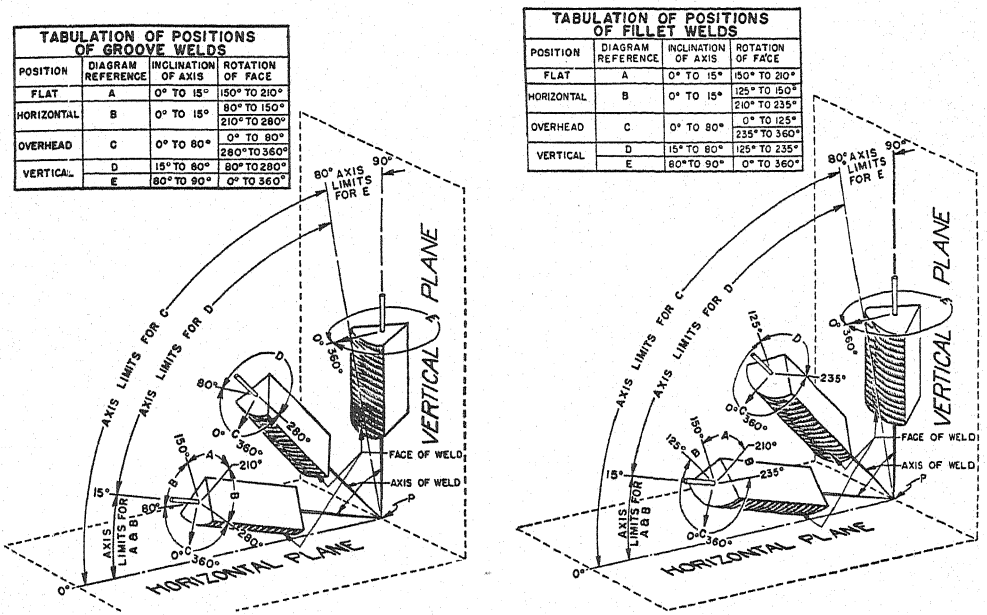
(*1*) Standard Specifications for Low-Carbon Nickel-Steel Plates for Boilers

[3] 1939 Book of A.S.T.M. Standards, Part I, p. 41.
[4] *Ibid.*, p. 1.

and Other Pressure Vessels (A.S.T.M. Designation: A 203),[5] grade C.

(2) Standard Specifications for Molybdenum-Steel Plates for Boilers and Other Pressure Vessels (A.S.T.M. Designation: A 204),[6] grade C.

(*c*) For electrodes smaller than $\frac{1}{8}$ in., the all-weld-metal tension test is not



(*a*) Groove Welds. (*b*) Fillet Welds.

The horizontal reference plane is taken to lie always below the weld under consideration.
Inclination of axis is measured from the horizontal reference plane toward the vertical.
Angle of rotation of face is measured from a line perpendicular to the axis of the weld and lying in a vertical plane containing this axis. The reference position (0 deg.) of rotation of the face invariably points in the direction opposite to that in which the axis angle increases. The angle of rotation of the face of weld is measured in a clockwise direction from this reference position (0 deg.) when looking toward point "*P*".

FIG. 2.—Position of Welds.

practical and the strength of these sizes shall be judged by the strength of $\frac{1}{8}$-in. or larger electrodes of the same classification.

(*d*) For electrodes $\frac{1}{8}$ in. and larger a test plate shall be prepared as shown in Fig. 1. The plate shall be insulated from the welding bench by $\frac{1}{2}$ in. of asbestos during welding. After the joint has been tacked, the assembly shall be heated in boiling water for 5 min. prior to welding. After depositing each pass, the assembly shall be left on the asbestos to cool in still air for 10 min., and then immersed in boiling water for 5 min. Each subsequent pass shall be deposited immediately after removal from boiling water. After the last pass, the assembly shall be removed from boiling water after the 5-min. period. If it is necessary to interrupt the pass sequence prescribed above, the assembly shall be removed from boiling water after a 5-min. period and allowed to cool in still air at room temperature. When ready to resume work, the assembly shall be preheated in boiling water for a period of 5 min. The work shall be done at room temperature of not less

[5] 1939 Book of A.S.T.M. Standards, Part I, p. 69.
[6] *Ibid.*, p. 73.

TABLE I.—TENSILE REQUIREMENTS OF DEPOSITED METAL.

Electrode Classification Number	Capable of Producing Satisfactory Welds in Positions Shown[a]	General Description	Treatment of Welded Specimen[b]	Tension Test Requirements of Material Deposited from 1/8 to 5/16-in. Electrodes[c]		
				Tensile Strength, min., psi.	Yield Point, min., psi.	Elongation in 2 in., min., per cent
E4510	F, V, OH, H	Wire with coating applied before drawing.	NSR	45 000	....	5
E4511	F, V, OH, H	Wire with light coating applied after drawing.	NSR	45 000	....	5
E4520	H-Fillets, F	Wire with coating applied before drawing.	NSR	45 000	....	5
E4521	H-Fillets, F	Wire with light coating applied after drawing.	NSR	45 000	....	5
E6010	F, V, OH, H	Heavy covering, useful with d.c., electrode positive only.	SR NSR	60 000 62 000	47 000 52 000	27 22
E6011	F, V, OH, H	Heavy covering, useful with a.c. only.	SR NSR	60 000 62 000	47 000 52 000	27 22
E6012	F, V, OH, H	Heavy covering, usually used with electrode negative, d.c. or on a.c.	SR NSR	60 000 62 000	47 000 52 000	22 17
E6013	F, V, OH, H	Heavy covering, usually used on a.c.	SR NSR	60 000 62 000	47 000 52 000	22 17
E6020	H-Fillets, F	Heavy covering, usually used with electrode negative or a.c. for fillets, and electrode positive or a.c. for flat welding.	SR NSR	60 000 62 000	47 000 52 000	30 25
E6030	F	Heavy covering, usually used with electrode positive on d.c., or with a.c.	SR NSR	60 000 62 000	47 000 52 000	30 25
E7010	V, F, OH, H	Heavy covering, useful with d.c., electrode positive only.	SR NSR	70 000 72 000	57 000 62 000	22 17
E7011	F, V, OH, H	Heavy covering, useful with a.c. only.	SR NSR	70 000 72 000	57 000 62 000	22 17
E7012	F, V, OH, H	Heavy covering, usually used with electrode negative, d.c. or on a.c.	SR NSR	70 000 72 000	57 000 62 000	20 15
E7020	H-Fillets, F	Heavy covering, usually used with electrode negative or a.c. for fillets, or electrode positive or a.c. for flat welding.	SR NSR	70 000 72 000	57 000 62 000	25 20
E7030	F	Heavy covering, usually used with electrode positive d.c., or with a.c.	SR NSR	70 000 72 000	57 000 62 000	25 20
E8010	F, V, OH, H	Heavy covering, useful with d.c. electrode positive only.	SR	80 000	67 000	19
E8011	F, V, OH, H	Heavy covering, useful with a.c. only.	SR	80 000	67 000	19
E8012	F, V, OH, H	Heavy covering, usually used with electrode negative, d.c. or on a.c.	SR	80 000	67 000	17
E8020	H-Fillets, F	Heavy covering, usually used with electrode negative or a.c. for fillets, or electrode positive or a.c. for flat welding.	SR	80 000	67 000	22
E8030	F	Heavy covering, usually used with electrode positive d.c., or with a.c.	SR	80 000	67 000	22

TABLE I.—*Concluded.*

Electrode Classification Number	Capable of Producing Satisfactory Welds in Positions Shown[a]	General Description	Treatment of Welded Specimen[b]	Tension Test Requirements of Material Deposited from 1/8 to 5/16-in. Electrodes[c]		
				Tensile Strength, min., psi.	Yield Point, min., psi.	Elongation in 2 in., min., per cent
E9010	F, V, OH, H	Heavy covering, useful with d.c. electrode positive only.	SR.....	90 000	77 000	18
E9011	F, V, OH, H	Heavy covering, useful with a.c. only.	SR.....	90 000	77 000	18
E9012	F, V, OH, H	Heavy covering, usually used with electrode negative, d.c. or on a.c.	SR.....	90 000	77 000	16
E9020	H-Fillets, F	Heavy covering, usually used with electrode negative or a.c. for fillets, or electrode positive or a.c. for flat welding.	SR.....	90 000	77 000	20
E9030	F	Heavy covering, usually used with electrode positive d.c., or with a.c.	SR.....	90 000	77 000	20
E10010	F, V, OH, H	Heavy covering, useful with d.c. electrode positive only.	SR.....	100 000	87 000	16
E10011	F, V, OH, H	Heavy covering, useful with a.c. only.	SR.....	100 000	87 000	16
E10012	F, V, OH, H	Heavy covering, usually used with electrode negative, d.c. or on a.c.	SR.....	100 000	87 000	14
E10020	H-Fillets, F	Heavy covering, usually used with electrode negative or a.c. for fillets, or electrode positive or a.c. for flat welding.	SR.....	100 000	87 000	18
E10030	F	Heavy covering, usually used with electrode positive d.c., or with a.c.	SR.....	100 000	87 000	18

[a] The abbreviations F, V, H, OH, and H-Fillets indicate welding positions, as follows:
F—Flat, H—Horizontal,
V—Vertical, OH—Overhead, and
H-Fillets—Horizontal Fillets.

[b] The abbreviations SR and NSR signify stress-relieved and non-stress-relieved, respectively. Stress-relieving when prescribed in these specifications is for the purpose of developing the fundamental properties of the weld metal unaltered by locked-up stress. Values obtained from stress-relieved welded specimens are about 5 per cent lower in tensile strength and 10 to 20 per cent higher in elongation than those of non-stress-relieved specimens. The fact that an electrode test requires stress-relief signifies only that it must develop the strength required regardless of stress-relief, and not that stress-relief must always be used in actual work. Stress-relieving shall be within the range of 1150 ± 25 F. for 1 hr. per inch of thickness. Specimens shall be heated in a suitable furnace at the rate of 300 to 350 F. per hour until a temperature of 1150 ± 25 F. has been attained. After this temperature has been reached, it shall be maintained for 1 hr. for each inch or fraction thereof of the maximum thickness of the section. The specimens shall be cooled at the same rate specified for heating and may be removed from the furnace when the temperature of the plates has reached 300 F.

[c] The tension test requirements of material deposited from 3/8-in. electrodes shall be the same as that indicated for 1/8 to 5/16-in. electrodes, except that the tensile strength and yield point shall be 95 per cent of that prescribed in Table I.

than 60 F. and in the flat position. Weaving shall be the full width of the groove except for the last layer, which shall be deposited in two passes. Test plates shall preferably be so supported that warping due to welding will not cause the finished test plate to be out of line by more than 5 deg. If test plates become warped more than 5 deg. they shall be straightened cold before being stress-relieved when required.

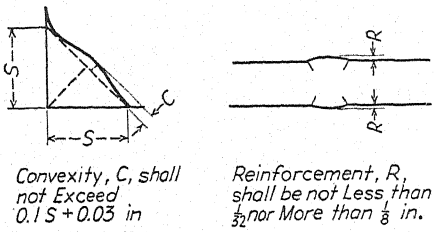
(*e*) Two all-weld-metal tension test specimens shall be machined from the finished test plate as shown in Fig. 1, and shall conform to the requirements as to tensile properties prescribed in Table I.

(*f*) If either specimen fails, another test plate shall be welded and both specimens shall conform to the requirements as to tensile properties prescribed in Table I.

(*g*) Electrodes in each classification shall be capable of producing satisfactory welds which will conform to the all-weld-metal tension test requirements prescribed in Table I, for the types of current and the welding positions listed in the table. Welding positions shall be determined from Fig. 2.

Weld Contour Tests

7. (*a*) For each classification and size of electrode, specimen butt and fillet welds shall be prepared with the types of current and the welding positions listed in Table I. The size and convexity of fillet welds and the height of



(*a*) Fillet Weld Profile. (*b*) Butt Weld Profile.

FIG. 3.—Acceptable Fillet and Butt Weld Profiles.

reinforcement of butt welds shall be measured (see Fig. 3) and shall conform to the following requirements: For fillet welds the convexity shall not exceed $0.1S + 0.03$ in., where S is the size of the fillet weld in inches; for butt welds the height of reinforcement shall be not less than $\frac{1}{32}$ in. and not more than $\frac{1}{8}$ in.

(*b*) The results shall be recorded and shall be furnished by the manufacturer to the purchaser upon request.

Face- and Root-Bend Tests of Welded Joints

8. For electrodes of the E60 and E70 classifications, face- and root-bend tests shall be made as prescribed in the following Paragraphs (*a*) to (*f*):

(*a*) The steel to be used for test plates shall conform to either of the specifications listed in Section 6 (*a*).

(*b*) For each classification of electrode, a test plate as shown in Fig. 4 shall be prepared in each position for which the electrode is suitable, as listed in Table I. The work shall be done at room temperature of not less than 60 F. No stress-relieving shall be performed on the test plate or on the specimens removed therefrom.

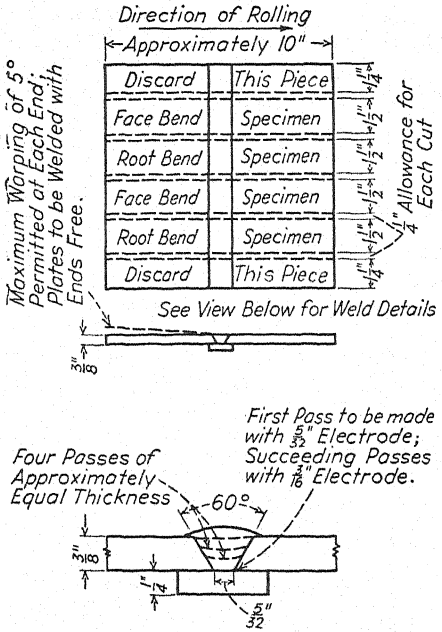
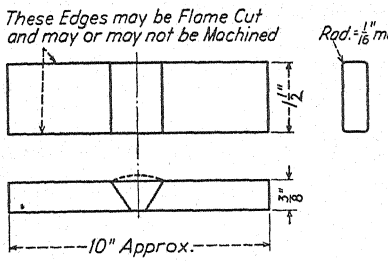


FIG. 4.—Requirements for Preparation of Test Plate for Face- and Root-Bend Tests.

(*c*) From each test plate there shall be removed two face-bend specimens and two root-bend specimens in the order shown in Fig. 4. The specimens shall be prepared for testing as shown in Fig. 5.

(*d*) Each specimen shall be bent in a jig having the working contour shown in Fig. 6, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving

the plunger member with relation to the die member. The specimen shall be placed on the die member of the jig with the weld at midspan. Face-bend specimens shall be placed with the face of the weld directed toward the gap and root-bend specimens shall be placed with the root of the weld directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a wire $\frac{1}{32}$ in. in diameter cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The



NOTE.—Weld reinforcement shall be removed flush with the surface of the specimen. Machining shall be done lengthwise of the specimen. The surface of the specimen to be tested shall be finely machined or ground.

FIG. 5.—Face- and Root-Bend Test Specimens.

specimen shall then be removed from the jig.

(*e*) The convex surface of each specimen shall be examined for the appearance of cracks or other open defects. The specimen shall be considered as having failed if a crack or other open defect, exceeding $\frac{1}{8}$ in. measured in any direction, is present after the bending. Cracks occurring on the corners of the specimen during testing shall not be considered.

(*f*) Electrodes of all sizes in each E60 and E70 classification shall be capable of producing satisfactory welds which will conform to the face- and root-bend test requirements prescribed in Paragraphs (*a*) to (*e*) above, for the types of current and the welding positions for which the electrodes are suitable, as listed in Table I.

Permissible Variations in Dimensions

9. (*a*) Covered electrodes for manual welding shall be bare or free from covering for a distance of about 1 in., but not more than $1\frac{1}{4}$ in., for making contact with the holder.

(*b*) The arc end of each electrode shall be sufficiently bare to permit easy striking of the arc, but the length of the bare

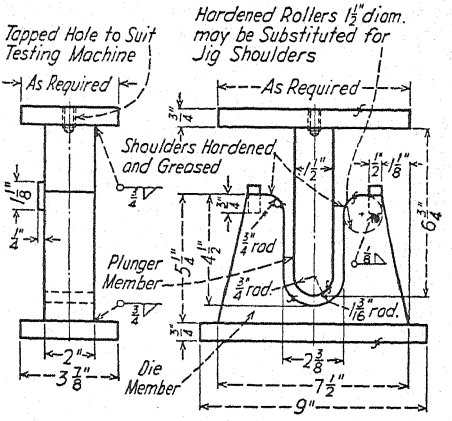


FIG. 6.—Guided-Bend Test Jig.

portion of the arc end, measured from the end to the point where the full cross-section of the coating obtains, shall not exceed one core-wire diameter or in any case be more than $\frac{1}{8}$ in.

(*c*) The diameter of the core wire shall not vary more than plus or minus 0.002 in. from the standard size specified. The length shall not vary more than plus or minus $\frac{1}{8}$ in. from that specified.

(*d*) The covering on covered electrodes of all sizes shall be concentric to the extent that the maximum core-plus-one-covering dimension shall not exceed the minimum core-plus-one-covering dimension by more than 3 per cent. The

concentricity shall be measured by any suitable means, such as the following:

The covering shall be removed from one side of the electrode (care being taken to insure that no metal is removed from the core) at about the middle of its length. The core-plus-one-covering dimension (which is the diameter of the core plus the thickness of the covering on one side) shall be measured with a micrometer. The covering shall be removed from the opposite side of the electrode at a point distant from the place where the covering was previously removed, and a similar measurement made. Two more pairs of measurements of the core-plus-one-covering dimension shall be made on planes at angles of 60 and 120 deg. from the plane of the former measurements. The pair of measurements which shows the greatest percentage of variation shall be used in determining the acceptability of the electrode.

Electrode Coverings

10. (*a*) The coverings shall, when cool, have sufficient electrical resistance to effectively insulate against a difference of potential of 100 v.

(*b*) The slag produced shall be readily removable.

Workmanship

11. (*a*) Lightly coated electrodes and the core of covered electrodes shall be of uniform quality and free from injurious segregation, oxides, pipe, seams, or other irregularities.

(*b*) On covered electrodes, the coverings shall be such that they are not readily damaged by ordinary handling and shall be of commercially uniform thickness and shall present a workmanlike appearance. Coverings shall be free from injurious scabs, blisters, abnormal pockmarks, bruises, or other surface defects.

Finish

12. The surface of lightly coated electrodes and the core of covered electrodes shall be smooth and free from harmful scale, oil, or grease.

Packing

13. Electrodes shall be suitably packed, wrapped, boxed, or crated to insure against injury during shipment or storage, as follows:

(*a*) Bundles of 50 lb. net weight,

(*b*) Boxes of 25 or 50 lb. net weight, and

(*c*) Coils or reels of approximately 150 or 200 lb. net weight.

Marking

14. All bundles, boxes, coils, or reels shall be legibly marked with the following information:

(*a*) Classification,

(*b*) Manufacturer's name and trade designation,

(*c*) Standard size and length, (weight instead of length in case of reels and coils), and

(*d*) Guarantee.

Guarantee

15. The manufacturer shall make tests at frequent intervals in accordance with the methods prescribed in these specifications, and shall guarantee that the electrodes in all sizes and classes conform to these specifications and each container shall be so marked. The manufacturer's responsibility shall be limited to replacement of any electrodes which do not conform to the requirements of these specifications.

CHAPTER 27B

Tentative Specifications for

IRON AND STEEL GAS-WELDING RODS[1]

Serial Designation: A 251 - 42 T

ISSUED, 1942[2]

This is a Tentative Standard and under the Regulations of the Cooperating Societies is subject to annual revision. Suggestions for revision should be addressed to the Headquarters of the A.S.T.M., 260 S. Broad Street, Philadelphia, Pa., or of the A.W.S., 33 W. 39th Street, New York, N. Y.

These Specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. (*a*) These specifications cover gas-welding rods for the welding of carbon and low-alloy steels of weldable quality.

NOTE.—In connection with the welding of low-alloy steels the requirements of these specifications pertain to the tensile strength and elongation of the deposited metal and not to high- or low-temperature characteristics, creep properties, or corrosion resistance.

(*b*) The rods are classified on the basis of the ultimate tensile strength of the deposited weld metal in the stress-relieved condition, as shown in Table I.

Manufacture

2. The rods may be made by any methods that will yield a product conforming to the requirements of these specifications.

Standard Sizes and Length

3. Standard length rods are 36 in., and standard diameters are as follows:

$\frac{1}{16}$ in.	$\frac{5}{32}$ in.	$\frac{5}{16}$ in.
$\frac{3}{32}$ in.	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.
$\frac{1}{8}$ in.	$\frac{1}{4}$ in.	

Chemical Composition

4. The rods shall conform to the following requirement as to chemical composition:

Sulfur, max., per cent	0.045

Tension Tests

5. Tension tests shall be made, using $\frac{3}{16}$ or $\frac{1}{4}$-in. welding rods, as prescribed in the following Paragraphs (*a*) to (*e*), these tests qualifying all sizes of welding rod made from the same melt of steel.

(*a*) The steel to be used for test plates shall conform to either of the following

[1] Under the standardization procedure of the two Societies, these specifications are under the jurisdiction of the A.S.T.M. Committee A-1 on Steel, and of the A.W.S. Filler Metal Specifications Committee.

[2] Accepted by A.S.T.M. Committee E-10 on Standards, April 28, 1942; approved by A.W.S. Board of Directors, May 7, 1942.

These specifications which comprise a portion of the former Tentative Specifications for Iron and Steel Filler Metal (Arc-Welding Electrodes and Gas-Welding Rods (A 205 - 37 T)) were published as tentative from 1937 to 1940.

specifications of the American Society for Testing Materials:

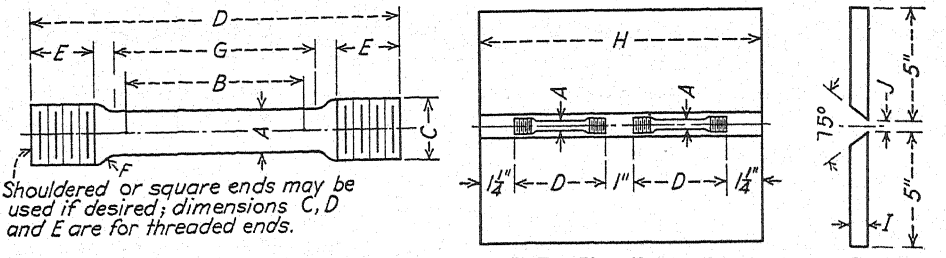
(*1*) Standard Specifications for Carbon-Steel Plates for Stationary Boilers and other Pressure Vessels (A.S.T.M. Designation: A 70),[3] and

(*2*) Standard Specifications for Steel for Bridges and Buildings (A.S.T.M. Designation: A 7),[4] open-hearth or electric-furnace steel.

(*b*) A test plate shall be prepared as shown in Fig. 1 (for welding rods of the GA65, GA60, GA50, GB65, and GB60 classifications) or Fig. 2 (for welding rods of the GB45 classification). The plate shall be insulated from the welding bench by asbestos during welding. After the joint has been tacked, the plate on both sides of the joint shall be heated for approximately 5 min. with a flame of the size and type to be used in welding the joint. The test plate shall then be welded using a maximum of five layers and having no layer exceeding $\frac{5}{16}$ in. in thickness. The weld metal shall be deposited with a backhand technique,

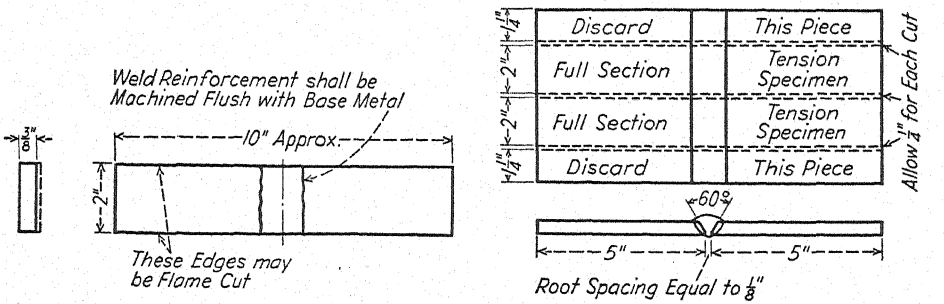
Dimensions of Test Plate and Tension Test Specimen, in.

A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
0.500 ± 0.01	2	¾	4¼	¾	⅜	2¼	12	¾	¼



(*a*) Tension Test Specimen. (*b*) Test Plate Showing Location of Test Specimens.

FIG. 1.—Requirements for Preparation of All-Weld-Metal Tension Test Specimens.



(*a*) Tension Test Specimen. (*b*) Test Plate Showing Location of Test Specimen

FIG. 2.—Requirements for Preparation of Full-Section Tension Test Specimens.

[3] 1939 Book of A.S.T.M. Standards, Part I, p. 41.
[4] *Ibid.*, p. 1.

using the size and type of flame recommended by the manufacturer of the welding rod. After depositing each layer, the plate shall be left on the asbestos to cool in still air for at least 15 min. The joint shall be welded completely but shall not have a reinforcement exceeding 20 per cent of the plate thickness. It is permissible to torch normalize the weld by reheating the weld metal above the critical temperature range. After the last pass, the plate shall be left on the asbestos until cold. The work shall be done at room temperature of not less than 60 F. and in the flat position. Test plates shall preferably be so supported that warping due to welding will not cause the finished test plate to be out of line by more than 5 deg. If test plates become warped more than 5 deg. they shall be straightened cold before being stress-relieved, when required.

(*c*) Two tension test specimens shall be machined from the finished test plate as shown in Fig. 1 (for welding rods of the GA65, GA60, GA50, GB65, and GB60 classifications) or Fig. 2 (for welding rods of the GB45 classification), and shall conform to the requirements as to tensile properties prescribed in Table I.

(*d*) If either specimen fails, another test plate shall be welded and both specimens shall conform to the tension test requirements prescribed in Table I.

(*e*) Welding rods in each classification shall be capable of producing satisfactory welds which will conform to the tension test requirements prescribed in Table I for all positions of welding.

Face- and Root-Bend Tests of Welded Joints

6. For all classifications of welding rods, except GB45, face- and root-bend tests shall be made, using $\frac{3}{16}$ or $\frac{1}{4}$-in. welding rods, as prescribed in the following Paragraphs (*a*) to (*f*), these tests qualifying all sizes of welding rod made from the same melt of steel.

(*a*) The steel to be used for test plates shall conform to either of the specifications listed in Section 5 (*a*).

TABLE I.—TENSILE REQUIREMENTS OF DEPOSITED METAL.

(Using $\frac{5}{16}$ or $\frac{1}{4}$-in. Welding Rods)

Welding Rod Classification Number	Plate Thickness, in.	Treatment of Welded Specimen[a]	Tension Test Requirements	
			Tensile Strength, min., psi.	Elongation in 2 in., min., per cent
GA65	¾	SR	65 000	20
		NSR	72 000	17
GA60	¾	SR	60 000	25
		NSR	62 000	20
GA50	¾	SR	50 000	28
		NSR	52 000	23
GB65	¾	SR	65 000	18
		NSR	72 000	15
GB60	¾	SR	60 000	20
		NSR	62 000	15
GB45	⅜	NSR	45 000[b]	..

[a] The abbreviations SR and NSR signify stress-relieved and non-stress-relieved, respectively. Stress-relieving when prescribed in these specifications is for the purpose of developing the fundamental properties of the weld metal unaltered by locked-up stress. Values obtained from stress-relieved welded specimens are about 5 per cent lower in tensile strength and 10 to 20 per cent higher in elongation than those of non-stress-relieved specimens. Stress-relieving shall be within the range of 1150 ± 25 F. for 1 hr. per inch of thickness. Specimens shall be heated in a suitable furnace at the rate of 300 to 350 F. per hour until a temperature of 1150 ± 25 F. has been attained. After this temperature has been reached, it shall be maintained for 1 hr. for each inch or fraction thereof of the maximum thickness of the section. The specimens shall be cooled at the same rate specified for heating and may be removed from the furnace when the temperature of the plates has reached 300 F.

[b] This value shall be obtained with the full-section tension test specimen shown in Fig. 2. All other values in this column shall be obtained with the all-weld-metal tension test specimen shown in Fig. 1.

(*b*) A test plate shall be prepared as shown in Fig. 3. The work shall be done at room temperature of not less than 60 F. and in the flat position. No stress-relieving shall be performed on the test plate or on the specimens removed therefrom.

(*c*) From each test plate there shall be removed two face-bend specimens and two root-bend specimens in the order shown in Fig. 3. The specimens shall be prepared for testing as shown in Fig. 4.

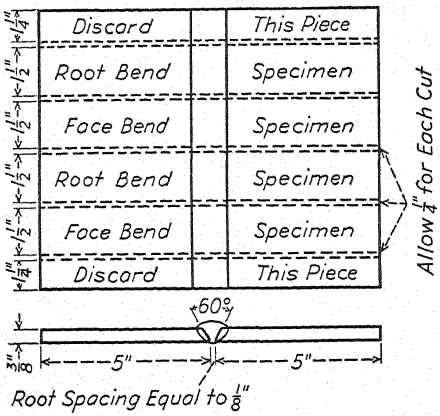
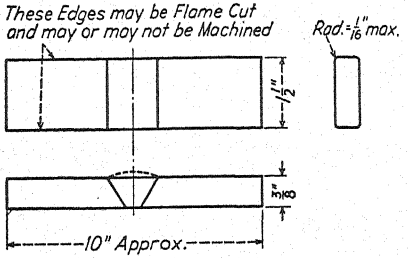


FIG. 3.—Requirements for Preparation of Test Plate for Face- and Root-Bend Tests.

(*d*) Each specimen shall be bent in a jig having the working contour shown in Fig. 5, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving the plunger member with relation to the die member. The specimen shall be placed on the die member of the jig with the weld at mid-span. Face-bend specimens shall be placed with the face of the weld directed toward the gap, and root-bend specimens shall be placed with the root of the weld directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a wire $\frac{1}{32}$ in. in diameter cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig.



NOTE.—Weld reinforcement shall be removed flush with the surface of the specimen. Machining shall be done lengthwise of the specimen. The surface of the specimen to be tested shall be finely machined or ground.

FIG. 4.—Face- and Root-Bend Specimens.

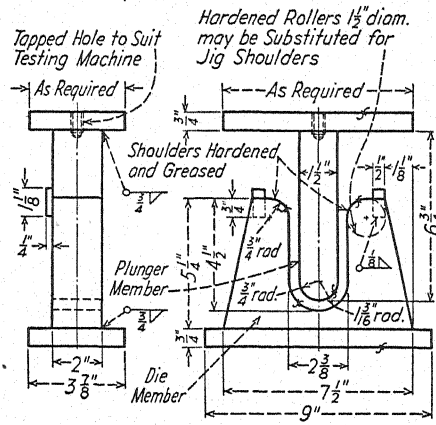


FIG. 5.—Guided-Bend Test Jig.

(*e*) The convex surface of each specimen shall be examined for the appearance of cracks or other open defects. The specimen shall be considered as having failed if a crack or other open defect, exceeding $\frac{1}{8}$ in. measured in any direction, is present after the bending. Cracks occurring on the corners of the specimen during testing shall not be considered.

(*f*) Welding rods of all classifications, except GB45, shall be capable of producing satisfactory welds which will conform to the face- and root-bend test requirements prescribed in Paragraphs (*a*) to (*e*) above, for all positions of welding.

Permissible Variations in Dimensions

7. The diameter of the rod shall not vary more than plus or minus 0.005 in. from the standard size specified. Cut lengths shall not vary from that specified by more than plus 0 or minus $\frac{1}{4}$ in.

Workmanship and Finish

8. (*a*) Rods shall be of uniform quality and free from injurious segregation, oxides, pipe, seams, or other irregularities.

(*b*) Rods shall be cold-drawn to a smooth finish, free from slivers, depressions, scratches, scale, lime, or foreign matter other than oil, except that rods may have a copper coating.

(*c*) The rods shall be carefully oiled with the minimum amount necessary to prevent rusting, except when copper-coated or otherwise treated to prevent rusting.

Packing

9. The rods shall be suitably packed, wrapped, boxed, or crated to protect against injury during shipment or under normal dry storage conditions, as follows:

(*a*) Bundles of 50 or 100 lb. net weight,

(*b*) Boxes or kegs of 50, 100, or 300 lb. net weight.

Marking

10. (*a*) Welding rods $\frac{1}{8}$ in. and over in diameter shall be marked or stamped with positive identification marks at intervals of not more than 18 in. Such marks shall be clearly distinguishable and shall identify the trade designation of the manufacturer or the classification number of the welding rod.

(*b*) All bundles, boxes, or kegs shall be legibly marked with the following information:

(*1*) Classification,

(*2*) Manufacturer's name and trade designation, and

(*3*) Standard size and length.

Guarantee

11. The manufacturer shall make tests at frequent intervals in accordance with the methods prescribed in these specifications, and shall guarantee that the rods in all sizes and classes conform to these specifications, and the marking of the classification number on the container shall be indication of this fact. The manufacturer's responsibility shall be limited to replacement of any rods which do not conform to the requirements of these specifications.

CHAPTER 27C

Tentative Specifications for
ALUMINUM AND ALUMINUM ALLOY METAL ARC WELDING ELECTRODES

ISSUED, 1942*

This is a Tentative Standard and under the Regulations of the Cooperating Societies is subject to annual revision. Suggestions for revision should be addressed to the Headquarters of the A.S.T.M., 260 S. Broad Street, Philadelphia, Pa., or of the A.W.S., 33 W. 39th Street, New York, N. Y.

These specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. These specifications cover coated or covered metal arc welding electrodes for welding aluminum and the aluminum alloys. The coating or covering is referred to in these specifications as "covering."

Manufacture

2. The electrodes may be made by any methods that will yield a product conforming to the requirements of these specifications.

Standard Sizes and Lengths

3. Standard sizes and lengths of electrodes are as shown in the following table. In all cases, standard size refers to the diameter of the core wire.

Standard Sizes, Diameter of Core Wire, in.	Standard Lengths, in.
1/32, 1/8, 5/32, 3/16 and 1/4	14
5/16 and 3/8	18

* Approved by A. W. S. Board of Directors, May 7, 1942. Acceptance by A.S.T.M. not received at time of publication.

Chemical Composition

4. The electrode core wire shall conform to the requirements as to chemical composition prescribed in Table I.

TABLE I.—CHEMICAL REQUIREMENTS.

NOTE.—Analysis shall regularly be made only for the elements specifically mentioned in this table. If, however, the presence of other elements is suspected, or indicated in the course of routine analysis, further analysis shall be made to determine that these other elements are not in excess of the amount specified.

	Electrode Classification Number	
	A1–2	A1–43
Copper, max., %	0.20	0.30
Magnesium, max., %	....	0.03
Manganese, max., %	0.05	0.05
Silicon, %	[a]	4.5 to 6.0
Iron, max., %	[a]	0.80
Zinc, max., %	....	0.03
Titanium, max., %	....	0.20
Aluminum, %	99.00 to 99.50	Remainder
Other elements, max., %:		
Each	0.03	0.03
Total	0.10	0.10

[a] Silicon plus iron, 1.0 max., %.

Weld Tests

5. (*a*) To determine the suitability of the electrodes for producing welds of

adequate strength, ductility and soundness, a test plate shall be welded as prescribed in the following Paragraphs (*b*) to (*d*) and tested as prescribed in Sections 6 and 7.

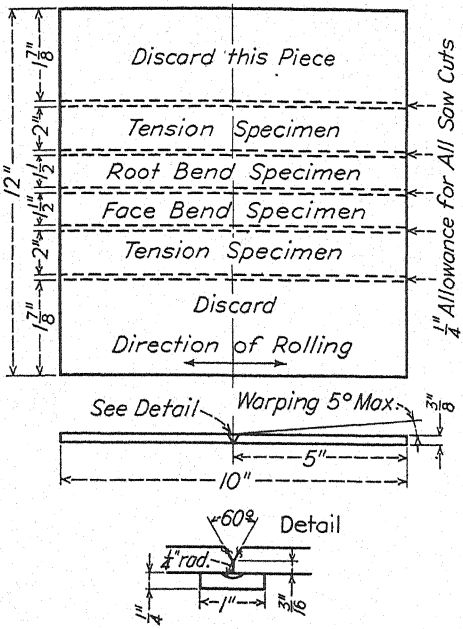


Fig. 1—Requirements for Preparation of Weld Test Plate

(*b*) The performance of electrodes of sizes smaller than $^5/_{32}$ in. shall be judged by the performance of $^5/_{32}$-in. electrodes of the same classification, and of electrodes of sizes larger than $^1/_4$ in., by the performance of $^1/_4$-in. electrodes of the same classification.

(*c*) The test plate shall be prepared as shown in Fig. 1, using the size of electrode prescribed in Section 5 (*b*). The material for the test plate shall conform to the following specifications of the American Society for Testing Materials:

(1) For testing electrodes of classification No. Al-2, Tentative Specifications for Aluminum Sheet and Plate (A.S.T.M. Designation: B 25).[1]

(2) For testing electrodes of classification No. Al-43, Tentative Specifications for Aluminum-Manganese Alloy Sheet and Plate for Use in Welded Pressure Vessels (A.S.T.M Designation: B 126).[2]

(*d*) The test plate shall be preheated before welding to a temperature between 350 and 400 F. All welding shall be done from one side in the flat position. No stress-relieving or other thermal treatment shall be done after welding.

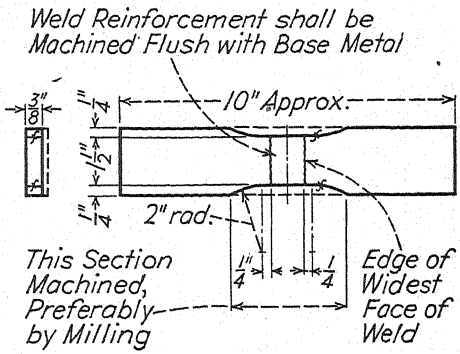


Fig. 2—Tension Test Specimen

Reduced-Section Tension Tests

6. (*a*) Two reduced-section tension test specimens shall be machined from the finished test plate as shown in Fig. 2.

(*b*) Before testing, the least width and corresponding thickness of the reduced section shall be measured in inches. The cross-sectional area shall be obtained by multiplying the width by the thickness. The specimen shall

[1] 1941 Supplement to Book of A.S.T.M. Standards, Part I, p. 326.

[2] 1940 Supplement to Book of A.S.T.M. Standards, Part I, p. 329.

be ruptured under tensile load and the maximum load in pounds shall be determined. The tensile strength in pounds per square inch shall be obtained by dividing the maximum load by the cross-sectional area.

(*c*) The tensile strength of each specimen shall conform to the following requirements:

	Electrode Classification Number	
	A1–2	A1–43
Tensile strength, min., psi.	12,000	14,000

Face- and Root-Bend Tests

7. (*a*) One face-bend and one root-bend specimen shall be machined from the finished test plate as shown in Fig. 3.

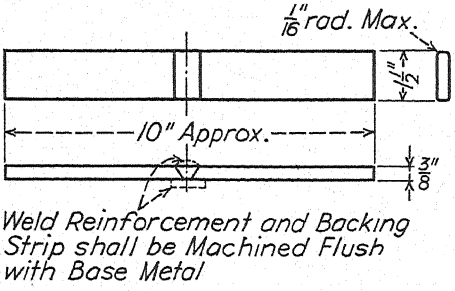


Fig. 3—Face- and Root-Bend Test Specimens

(*b*) Each specimen shall be bent in a jig having the working contour shown in Fig. 4, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving the plunger member with relation to the die member. The specimen shall be placed on the die member of the jig with the weld at midspan. Face-bend specimens shall be placed with the face of the weld directed toward the gap, and root-bend specimens shall be placed with the root of the weld directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a wire 1/32 in. indiameter cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig.

(*c*) The convex surface of the specimen shall be examined for the appearance of cracks or other open defects. The specimen shall be considered as having failed if a crack or other open defect, exceeding 1/8 in. measured in any direction, is present after bending.

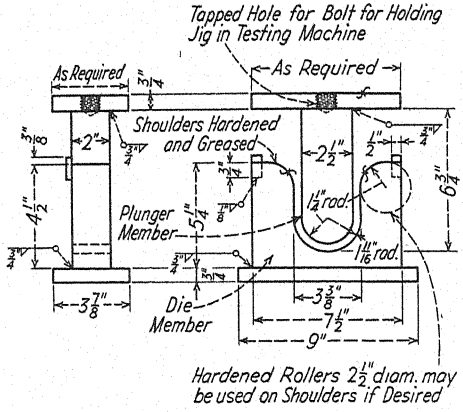


Fig. 4—Guided-Bend Test Jig

Cracks occurring on the corners of the specimen during testing shall not be considered.

Permissible Variations in Dimensions

8. (*a*) Electrodes shall be bare or free from covering for a distance of about 1 in., but not more than 1 1/4 in., for making contact with the holder.

(*b*) The arc end of each electrode shall either be bare or the covering easily removable with the fingers to permit easy striking of the arc. The length of any bare portion of the arc end, measured from the end to the

point where the full cross-section of the coating obtains, shall not exceed one core-wire diameter or in any case be more than $^1/_8$ in.

(*c*) The diameter of the core wire shall not vary more than plus or minus 0.005 in. from the standard size specified. The length shall not vary more than plus or minus $^1/_8$ in. from that specified.

Electrode Coverings

9. (*a*) Electrodes shall be suitable for making butt and fillet welds in the flat position and for making butt welds in the vertical position.

(*b*) The coverings shall have sufficient electrical resistance, at or below 100 F., to effectively insulate against a difference of potential of 100 v.

(*c*) The coverings shall be consumed uniformly on all sides during welding and shall not blister or burn back from the core wire.

(*d*) The slag produced shall be readily removable.

(*e*) The fumes given off from the covering when used in well-ventilated places shall not be injurious to the health of the welding operator.

(*f*) The coverings shall not blister when heated to 400 F.

Workmanship and Finish

10. (*a*) The core of electrodes shall be of uniform quality and free from injurious segregation, oxides, pipe, seams, or other harmful defects.

(*b*) The coverings on electrodes shall be such that they are not readily damaged by ordinary handling and shall be of commercially uniform thickness and shall present a workmanlike appearance. Coverings shall be free from injurious scabs, blisters, abnormal pockmarks, bruises or other surface defects.

Packing

11. (*a*) Electrodes shall be suitably packed, wrapped, boxed or crated to insure against injury during shipment or storage. The method of packaging shall be such as to protect the flux coating from absorbing moisture. All packages shall be dated at the time of packing.

(*b*) Standard packages shall be 1 or 10 lb. One-pound packages shall be packed in moisture-resistant wrappings. Ten-pound packages shall be packed in moisture-resistant wrappings, or shall be hermetically sealed, containing ten one-pound packages in moisture-resistant wrappings.

Marking

12. All bundles, packages or boxes shall be legibly marked with the following information:

(*a*) Name of article,

(*b*) Classification number,

(*c*) Manufacturer's name and trade designation,

(*d*) Standard size, length, and net weight,

(*e*) Date of packing, and

(*f*) Guarantee.

Guarantee

13. The manufacturer shall make tests at frequent intervals in accordance with the methods prescribed in these specifications, and shall guarantee that the electrodes in all sizes and classes conform to these specifications and each container shall be so marked. The manufacturer's responsibility shall be limited to replacement of any electrodes which do not conform to the requirements of these specifications.

CHAPTER 28

TRAINING OF WELDING OPERATORS*

Training Within the Plant, Training Outside the Plant, Welding Training in the Vocational School, Commercial Welding Schools, Minimum Requirements, a Cooperative Program of Training.

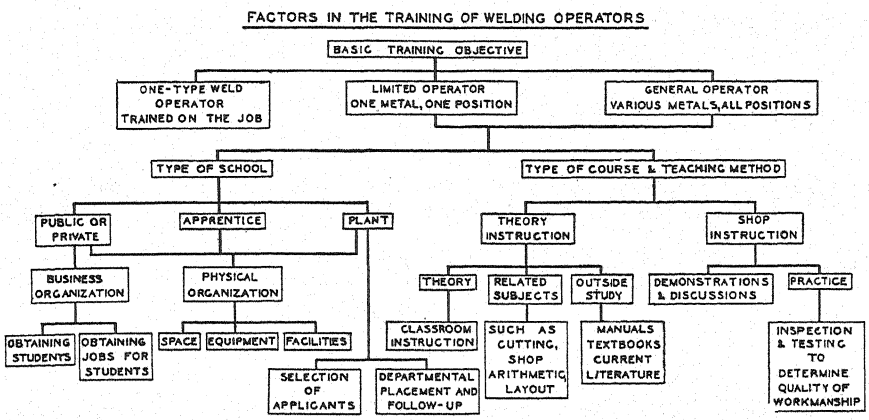
IT HAS been only within the last few years that facilities for training welding operators have been made generally available. Prior to this time, most employers with programs involving any large increase in welding operators were forced to accomplish their own training. The necessity for greater facilities for training has now been recognized by the public school system, and the rich field for training has naturally encouraged private enterprise along the same line. With a number of alternatives in method available, the employer must now determine the best means to obtain, or train, the operators he needs. This problem has no simple or general answer, as will be shown, for it depends upon the industry, the product, the plant itself and its geographic location, and many factors peculiar to the trade or art of welding.

In the first place, as yet it is impossible to define the term "welder" or "welding operator." Aside from the obvious distinction between the gas-welding operator and the arc-welding operator, the definition and job specifications of the term vary between one industry and another and even greatly between individual plants in the same industry. In one plant, for example, all arc-welding work may be positioned and all welding accomplished downhand, using large electrodes and alternating current. A first-class operator with years of experience in this shop will be of limited and perhaps no value on the ways of a shipyard, where all welding may be done with direct current and a very large part of it in the vertical and overhead positions. In one plant, a gas-welding operator may be employed exclusively on ferrous metals while in another, gas welding may be used only on aluminum, brass or other non-ferrous materials. An operator may be highly skilled in welding thin sheet and have no training or experience in heavy plate fabrication or pipe welding. Welding has grown too rapidly to have its classifications and job specifications determined.

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While many of the processes and the applications within a process have much in common and rest upon the same fundamentals, a man trained only in those fundamentals has still far to go before qualifying as a welding operator and being of value in any plant.



Assuming that an employer has developed definite job specifications, the paramount question is the best and quickest method to obtain an operator to perform work to those specifications. Generally speaking, training may be accomplished by two general methods or a combination of these two: (1) within the plant itself, and (2) by outside schools operated either under public or private direction and funds (vocational or defense schools) or the private or commercial welding school (operated for profit).

TRAINING WITHIN THE PLANT

In this method, the employer selects the trainees, provides the space, equipment, materials, instructors, and has complete control over the methods and subject matter. Both instruction and qualification for the minimum requirements of the plant, as well as the future upgrading, are coordinated and directed towards the specific requirements of that plant or its separate departments.

Advantages: (*a*) Plant standards and methods are impressed on the student from the beginning.

(*b*) The course is naturally designed to cover every essential point and methods peculiar to the plant without extraneous material.

(*c*) Much training can be coordinated with production work and part of the training is done on the job.

Disadvantages: (*a*) Space and equipment to be devoted solely to training are frequently at a premium.

(*b*) Unless the training program is a very large one, the overhead, as well as the direct cost, is high.

(*c*) The selection of trainees is in itself a major problem and the turnover is frequently high. Determination of aptitude without a fair period of instruction is difficult and much time is lost in proving adaptability.

(*d*) A certain number of "graduates" on whom much time and money have been expended inevitably drift to other plants.

(*e*) The problem of wages during training hours and occupation during some part of each day, since the number of hours per day which a student can practice effectively is limited, is often difficult or vexing.

Without regard to its relative merit, or the advantages or disadvantages, training within the plant is frequently the only method available due to the geographical location of the plant with no other training facilities at hand. While there are naturally many variations within this general method, a system typical of the plant school method of training arc welding operators is that in effect at a midwestern manufacturing plant. This company has found that to start with a man who has had no previous welding experience and train him specifically in the company's methods of fabrication is as satisfactory from all points of view as any other way of securing welding operators.

The first step is the hiring of the man for the definite purpose of learning to weld. Such a man is selected by the Personnel Department after he has qualified by meeting the requirements of mentality, education and character expected of such an employee. He must also pass a rigid physical examination. No previous experience in welding or related to welding is required nor especially desired.

After the student operator has been hired he is instructed in the safety practices carried out in the plant, with special emphasis on the wearing of goggles, protection from arc burn and the care of small burns. The welding instructor then assumes responsibility for the student operator. His first consideration is to familiarize the student with the instructional department and to assign a locker to him. The student is then taken to the tool room where tool checks, a slagging hammer, electrode stock pot, chipping chisel, and weld gage are issued to him. He then goes to the stock room where he equips himself with safety goggles, welding helmet, gloves, sleeves and apron. The welding instructor assists him in adjusting his equipment to fit and instructs him in the processes of changing helmet lens cover glasses and other such small, but important matters.

A machine in the instruction department is assigned to the student. The instructor explains the care of the cables, holder and machine and has the student start, stop and adjust the machine. Safety precautions are stressed pointedly again at this stage. Actual welding practice then is begun. The process of striking, holding and breaking an arc are first demonstrated by the instructor and then the student tries his hand at it. The next step is to lay a bead of weld metal in a straight line on a flat plate. Following that comes instruction in the process of stopping a bead, changing electrodes and starting the bead again with emphasis on fusing the new bead smoothly and soundly to the first deposit. The student is taught from the very beginning to melt his electrodes down to a $1^1/_2$-in. butt which he deposits in a small compartment in his electrode stock pot and

later returns to the stock room when he checks out another supply of electrodes.

The theoretical part of the student's training also is begun the first day. The student is given his copy of the textbook and a supplementary sheet with a questionnaire covering both the first lesson in the book and the supplementary lesson sheet. The supplementary sheet is designed to start the student in his welding experience with the consciousness of welding directions presented as symbols on a blueprint. The reading of the textbook and answering of the questions for each lesson is done by the student at home or at the plant, and the questionnaires are corrected by the instructor and handed back to the student as fast as the student desires to turn them in. At least one lesson a week is required under normal circumstances.

Six to eight weeks, depending on the student, are spent in practice welding under the close supervision of the welding instructor. After he can strike and hold an arc and lay a neat sound bead with one or more breaks and starts in it, the student begins to learn to tack weld pieces and to weld them soundly together. The butt joint and the positioned fillet welds come first. Proper arc length, position of electrode and manipulation of the arc are demonstrated by the instructor and then practiced until mastered by the student. Welds which have been deposited are carefully slagged, brushed, examined and criticized. The effect of porosity, undercut, overlap and excess or lack of heat are demonstrated by pointing out the visible defects and then by actually breaking the weld, so that the student can see what effect various flaws actually have on a welded joint.

The more difficult welds follow as soon as the student is skilful enough to undertake them. Multi-pass positioned fillet welds acquaint the beginner with the effects of accumulated heat, the need for cleaning of each pass, how much metal can be deposited in one pass with certain sized electrodes and how to get complete fusion, penetration and desirable appearance.

Horizontal fillet welds are practiced next, with frequent breaking of the specimen welds to demonstrate need for proper manipulation to get good fusion on the perpendicular leg of the weld.

Next in succession are semi-vertical and vertical welds built from the bottom up in one, two or more passes; or down in many passes. Horizontal butt welds, overhead butt and fillet welds and chamfered welds in all positions are successively studied in detail.

Almost all of this practice welding is done on small sections of plate cut for the purpose, although a few of the more advanced students sometimes can weld some of the more simple joints on an order of factory tote bins or some similar factory equipment. The different types of electrodes commonly used in the shop, their specialized purpose and the characteristics of each under different conditions are learned during this practice.

During the first six to eight weeks of practice, and for four to six weeks after he begins welding on production items, the student is studying the theoretical side of his work. The subject matter covers the theory of the welding machine, general terms and names associated with welding, the mechanics of depositing metal by means of an electrode and arc, strength of welds and weld metal, bare electrodes and coated electrodes. All of this general theory is correlated with the manual welding practice, first

by the welding instructor's personal contact with the student, and next by the supplementary sheets and questionnaire on the lessons.

Some of the later lessons (there are forty questionnaires and three major examinations over sections of the course) are devoted to the use of special welding electrodes such as hard facing, special high tensile electrodes and the welding of special metals. This phase of the course is quite theoretical but forms a basis for the special work which some of the operators later do, and serves to widen the student's knowledge of the possibilities of his craft.

The last eight lessons of the formal study course are devoted entirely to the description and teaching of the system of welding symbols. The first lesson is devoted to a general discussion of welding symbols and their purposes; the second and third explain the arrow base line, location, size and cross-sectional view showing the types of welds; the fourth is devoted to symbols showing the position in which the weld shown is to be deposited and the number of passes to be used; the fifth covers special classes of welds; and the sixth, seventh and eighth present the remaining portion of the symbol system which specifies the size of electrode, type of electrode and machine setting for each pass of the weld. A final examination covers the eight welding symbol lessons. Ordinarily the student has been welding on the simplest production work in the shop for from one to two months by the time he finishes his course on welding and welding symbols.

The progression from the manual practice stage in the instruction department to the first production job in the shop is an important one. The regular procedure is to go from practice welding to the welding of simple structures which are positioned for welding and are welded in sufficient numbers to maintain a full time job for several new welding operators. The welding is simple, yet has variety in size of weld, thickness of material and length of weld.

The student meets several new factors when he goes from the instructional department to the regular welding as a shop operator and for that reason is given close personal attention for a few days by one of the shop instructors. The experience of having his work examined by an inspector is sometimes upsetting to the new operator. Also, as a production welder, the new man is initiated into the experience of working for a bonus, and of following specified procedures. The departmental foreman and the departmental welding instructor guide and counsel the new operator in these problems.

After three to four months of welding the simplest structures the operator is usually placed in a department in which various small structures are fabricated. An experienced man sets up the structures in fixtures and tack welds them together, and the new man welds them. The work provides a greater variety of welding than simple box sections, and another departmental welding instructor carefully tutors the operator in the new situations which he has to meet.

After four to six months of experience in the small parts welding department, the operator is usually sufficiently skilled to be placed in one of several departments which fabricate the main structures. As a welding operator in these departments, he is usually teamed with an experienced man. Together they set up the structure in a fixture and then weld it in

the same fixture, or a special welding fixture which allows for more favorable positioning. This type of work further widens the experience of the operator, by giving him a wider variety of problems. At that stage of training the learning operator really begins to become proficient in the use of the arc as a universal tool for fabrication.

After several months of experience in one or several of these structure fabricating departments, the average operator has acquired the knowledge and skill which enable him to do most of the ordinary welding which is encountered in the factory. With a short period of time allowed for his learning the special fixtures for the job, studying the prints and practicing on the job he can usually perform the processes in the normal time required by an average operator and with a degree of skill which meets the standards of quality required by the job. Real proficiency, such as the ability to make special set-ups and welding without fixtures, requires more practice and experience. At the end of from twenty-four to thirty months his individual preferences, abilities and inclinations tend to direct him toward the place in the organization for which he seems best fitted.

TRAINING OUTSIDE THE PLANT

Vocational and private or commercial schools operated for profit have many problems in common, most of them springing from the one major difficulty—the wide variation in job requirements. Both must be able to show a record of successful placement of men in industry to survive.

From the standpoint of industry, the advantages of training outside the plant are as follows:

(*a*) Plant space and equipment which may be badly needed for production work are not required purely for instruction.

(*b*) The employer is relieved of the task of selecting trainees and the turnover in training. The employer is also saved all or part of the high cost of training which in general may well be from $200 to $500 per man.

The disadvantages:

(*a*) The lack of uniformity and standards in training methods.

(*b*) The wide variation in the caliber of instruction prevalent in both public and private schools.

(*c*) Particularly in public schools, there is little opportunity to exercise selection in the enrollment of trainees.

(*d*) Although a graduate of a course which meets the employer's specifications, a man lacks all shop experience.

WELDING TRAINING IN THE VOCATIONAL SCHOOL

In the development of programs for the training of operators for welding, consideration must be given to (1) the adequacy of relationships to be established between industry and school agencies, (2) wise selection of those to be trained, (3) modern equipment for school shops and classrooms, (4) organization of a course of study adequate to meet the needs of the field to be served, (5) accurate and reliable instructional material, (6)

properly qualified instructors, (7) checking results of instruction and (8) provision for placement of graduates.

High standards in the above eight divisions are important and actually essential to the success of the program whether the training is of the trade-preparatory type, training boys on an all-day trade-preparatory basis for later entrance upon employment in some specialized field, or of the trade extension type, training boys and older men on an evening trade-extension basis for greater efficiency in the work at which they are already employed.

Likewise, whether the program is one organized as a part of the public schools or a private trade school, the same basic standards should be maintained.

Relationship Between School and Industry

In the organization and maintenance of progress for the training of welding operators, desired results can be achieved only when there is established and maintained the right kind of relationship between school agencies, employers and labor. In some states the state education law makes mandatory advisory boards for vocational education in all cities and school districts maintaining vocational training programs. Such local advisory boards are charged with the responsibility of making studies and surveys for the purpose of determining needs for specific types of vocational training, establishing subcommittees to assist in the work of preparing studies and reports for the board of education regarding vocational training needs and promoting generally the establishment of vocational programs in the community.

In small towns and cities, one advisory board representative of industry and labor may meet the need for all industries. In larger cities, sub-advisory boards representing each of the major industries are appointed to work under the general direction of the advisory board provided for in the State Education Law. The importance of maintaining close working relationships between school agencies and industry through such advisory boards cannot be stressed too strongly. The maintenance or lack of maintenance of such coordination may mean the difference between complete success and total failure in programs for the training of welding operators.

Selection of Trainees

Choosing a beginner who is to be enrolled in a welding training program is as important as his training. If care is taken in the selection of persons to be trained, the development of first class welding operators is assured. From the point of view of the employer who is hiring a man to be enrolled in a trade extension type of training program, thirty minutes' time spent in the study of the man's qualifications will prove to be more valuable and less expensive than an insurance policy insuring his success. Careful selection of those to be trained will also eliminate those who are likely to be poor material because of either physical or mental disabilities.

Course of Study

Courses of study in general welding may be justifiable in large industrial areas where job welding shops or large manufacturing plants employ welding mechanics in adequate numbers to justify the establishment of such classes. In these cases the demand frequently is for combination electric and gas welders. Wherever the numbers to be trained justify it, however, separate classes should be established and separate courses of study provided for adequate training in both the electric and gas processes in the several fields—welding for sheet metal workers, welding for auto mechanics, welding for steam fitters, welding for aircraft workers, welding for structural steel workers, welding for factory maintenance men, and the like.

Full-time day courses of study should provide for instruction in shop practice and related technology and in non-vocational subjects. On the basis of a six-hour school day, 30-hour week, 15 hours should be devoted to shop practice and shop theory, $7^1/_2$ hours to related technology—including instruction in applied mathematics, applied science and applied drawing, and $7^1/_2$ hours to non-vocational subjects—including instruction in English, Civics and Industrial History.

For the evening trade-extension type of training program, the most effective course of study can be organized on the basis of short units. Here the purpose is that of giving instruction supplementary to the daily employment of persons over 16 years of age who have already entered upon employment.

Instructional Material

Drastic changes which have been made in new and improved tools and equipment, new processes which have been and are being developed and the trend toward standardization in procedure make necessary the constant revision of instructional material used in training programs. The instructor who fulfills his responsibility in this regard must be able to revise and write his own job instruction sheets. Much material, however, is available which can be used as basic reference material. The manufacturers of welding equipment and supplies have provided materials and engineering assistance which can be used to advantage. Some of the trade associations representing industries where the welding process has recently been introduced have developed materials which can be used to very good advantage in their specialized fields. Typical is the "Standard Manual on Pipe Welding" developed and published by the National Association of Heating and Air Conditioning Contractors.

Another important example of this is the Outline of Training Course for Oxy-Acetylene Welding and Cutting Operators that has recently been issued by International Acetylene Association. This course presents in outline form a series of self-contained lessons for training welding and cutting operators and inspectors. These lessons have been arranged in the ideal order for presenting a general course in welding, courses in aircraft welding and pipe welding, a general course in cutting, a course for structural steel cutting operators, or a course for inspectors. Each lesson contains an outline of theory or related material to be covered in lecture,

suggested assignments for outside study, recommendations for demonstrations and for practice exercises.

Instructional material must be of two kinds: (1) job instruction sheets and (2) related instructional material. Job instruction sheets contain step-by-step procedures in the doing of particular jobs, the listing of the apparatus tools and materials used in the job, together with safety precautions and other suggestions for the instructor and student. Related instructional material provides material and data on welding construction including the designing, laying out and fabrication of various types of welded joints, engineering and practical data, and specifications and standards covering the welding procedures to be followed in the particular field.

Because carelessness or lack of ability in the proper operation of welding equipment may result in excessive costs and even in hazards to both life and property, it is extremely important that rules and regulations having to do with precautions and safe practices be incorporated as a vital part of the instructional material.

Equipping the Welding School

Quarters to be assigned to a welding school depend, of course, on the space which may be available. A shop with a floor area of 1500 sq. ft., preferably about 50 ft. by 30 ft., will prove satisfactory for a welding work room to accommodate a maximum of eighteen students together with a small lecture room, wash room, a small store room and space for other materials and equipment needed in a welding training program. A lecture room is not essential since the welding work room may be used also for lectures and class instruction, or a related-subjects room may be available for use in another part of the school building. When it is desirable to assemble the class for shop talks, the space between the welding tables can be filled with folding chairs and the chairs removed after each lecture period.

Experience has shown that effective instruction can be given to a group of not more than eighteen students by one instructor. If instruction is to be given to larger numbers, the groups should be separated into two or more sections each with its own instructor.

Instructors

It goes without saying that the key to the success of the training program is a qualified instructor. A thoroughly capable instructor may make a success of a training program in spite of deficiencies in equipment, instructional material and other factors usually considered essential to a successful training program. A poor instructor, on the other hand, even when provided with the best in equipment, course of study and instructional material will produce mediocre results in a training program.

Instructors are of two kinds: those who teach the practical shop work and those who teach the related technology—related mathematics, related science and related drawing. These two types of instructors must possess different sets of training, experience and other qualifications. The instructor who teaches the practical shop work must, first of all, be a thor-

oughly qualified welding operator, and then he must be a good instructor. The instructor who teaches the related technology must, first of all, be a good engineer, and then he must be a good instructor.

Checking Results of Instruction

The knowledge, skill and judgment of pupils should be tested and found satisfactory at regular intervals before new work in the course of study can be undertaken. Testing serves three purposes. It determines the progress made by the individual, it acts as a review of the work covered in past instruction and it shows the instructor where his instruction has been weak in subject matter or in method, or both.

Testing for knowledge and skill involves two distinct operations. Separate tests must be given for each. This is necessary because the student may be well advanced in general knowledge of the welding process and yet have no skill, or he may be skillful in the operation of the welding torch or arc and yet be lacking in related information. Although tests for knowledge and skill require separate examinations, the content of each may be related to the other. A performance test may be given which involves the application of principles of the theoretical and technical phases of the welding process. Performance tests administered at intervals during the course of training should cover the important skilled operations which have been taught. Tests for knowledge can be made orally or written, while tests for skill must be made through the performance of specific operations selected for examination.

The results of these tests administered at periodical intervals during the course of training furnish a complete history of the student through his entire training period. These records constitute an improvement record or a record of progress and should be kept from the time the student is first tested until he has completed his entire period of training. Accurate recording enables the instructor, the student and the prospective employer to know at any time the exact amount of progress which any student has made.

Provision for Placement of Graduates

In the case of evening trade-extension programs, students in training already have jobs. In the case of all-day trade-preparatory training programs, the school and instructor have a definite responsibility to the student for assistance in his satisfactory placement at the conclusion of his training program. The record of placement of the school is proof of the degree of effectiveness of the training program. If the right kind of relationship has been established and maintained between school and industry and if high standards have been maintained in connection with each of the other items mentioned here, the placement of graduates should follow as a matter of course.

COMMERCIAL WELDING SCHOOLS

There have been enough failures on the part of the commercial trade schools to justify the frequently expressed opinion that such schools are

not entirely a dependable source of welding operators. On the other hand, there have been enough genuinely successful schools established and operated over long periods, to indicate that it is perfectly feasible for a trade school to train welding operators properly for industry.

From the experience of schools that have successfully placed their graduates in industrial plants it may be briefly stated that successful operation has been accomplished largely by a common sense cooperative effort—the school making a definite effort to provide what the employer wants, and the employer making his wants definitely known to the school. Assuming that the school has ample facilities and a competent instruction staff, there is nothing to hinder this cooperative effort from resulting in a practical and workable solution of the employment problem. There are some matters of detail on which opinions may differ, but a brief discussion of the more important details will make it apparent that the problem of training needs only to be approached with some degree of flexibility.

The matter of the amount of time to be given to the training period is among the most controversial questions. It should be obvious therefore that the length of the training period cannot be stated categorically. It is true that a young man with a certain degree of aptitude can be shown in less than an hour how to hold an arc and to deposit metal. In exceptional cases the metal which he has deposited will be of really good quality. It would be ridiculous to say that such a student is a trained operator. The fact that he has sufficient aptitude so that he can master the bare fundamentals of depositing metal is encouraging evidence that he is good operator material. He is not ready to go to work. He needs many hours of practice in depositing metal in various positions. He needs this principally because it requires a high degree of concentration and care to make a consistently sound weld in any position. This imposes a strain on unaccustomed muscles. Only after a reasonable amount of practice can the student be expected to make a sustained effort such as a full day of welding requires. Further, there are numerous mistakes of manipulation which cause defects in welds. The student needs time to encounter these mistakes in his practice work, to study their causes and effects and to learn how these mistakes in manipulation can be avoided. Due to differences in the instruction techniques and in the considered objectives, the time required to develop an acceptable degree of employable skill will vary over a wide range.

Under some conditions, there is a tendency on the part of either the instructor, or the employer, or the student, to speed up the training program by increasing the length of the shop practice periods. Such procedure is of doubtful value, because when the beginner is kept practicing after he has reached the fatigue point and is working under unaccustomed strain, he is more likely to develop undesirable welding habits than he is to improve his welding ability.

Welding is primarily hand work. Regardless of the desirability that an operator know as much about the theory of his work as possible, the chief function of the welding school is to impart a certain degree of manipulative skill to the student. This skill involves a more or less complete control over the pool of molten metal into which the deposited metal flows under his guidance. When the student can exercise this control without undue

tension, and continue it with a uniform measure of skill throughout a normal working day, he is ready to go to work.

In areas where there is a great diversity of welding activities, the school management finds it difficult to decide on the scope of the practice exercises. The best solution is to select exercises which are representative of average conditions, taking care to include enough exercises on material of medium thickness so that the student can become thoroughly informed as to the nature of sound weld deposits and how to make them. There is more to be gained by learning to do a small number of exercises well than by a more or less superficial practice over a very wide and confusing range of materials.

When the student is "ready to go to work," he is by no means a finished operator. He needs weeks of work under shop conditions to become familiar with the various conditions encountered in practice, which are so widely different from the simple exercises performed in the instruction booth. In many cases the student after graduation is put to work first as a tack welder or on work which is of minor importance. This gives him an opportunity to get further practice under observation, and to observe what the requirements of more advanced work are and to develop his technique until it is satisfactory for the more advanced work. The length of time required for making such progress will always vary from plant to plant.

All of these observations point to the desirability of cooperation between the employer and the school management. It is usually a simple matter for the employer to arrange with the instructors to provide a certain number of students with any special exercise work that is typical of his plant conditions and operations. It is equally practical to arrange for special qualification tests at the end of the course so that a student who has the necessary aptitude and who has made satisfactory progress during the instruction period can demonstrate at the time of applying for employment that he is qualified to weld on the materials and in the positions which are particularly important for the specific job.

The desirability of instruction in the theory of welding, either by class work or by lectures, can scarcely be questioned. The operator who works with his hands alone is at a disadvantage in competition with one who works with both his hands and his head. However, it is not always practicable or possible to provide an elaborate schedule of theory work. Many schools have found a good solution by setting up enough lecture periods to cover the most necessary fundamentals. In any case where no class work or lecture work at all is possible, the instructor has the heavy responsibility of explaining all of the whys and wherefores of welding procedure to each student individually, and it may be extremely difficult to do this in a thorough and systematic manner.

There is a wide divergence in the details of methods used by successful welding schools. Many of them are exclusively devoted to welding instruction and others are departments of larger trade schools. Some of them appear to be better equipped than others. And there is a very great difference in the method of teaching theory. Yet they have some fundamental things in common. They recognize that the most important objective is the development of manipulative skill. They are careful to

observe the attitude and aptitude of the student. They familiarize themselves with the requirements of the employer and concentrate on developing the highest possible degree of employability in the students, and they do not certify the student as having satisfactorily completed the course until that student has demonstrated in the school his ability to pass one or more of the recognized qualification tests.

The equipment of the school for practical training should by all means be of ample capacity for practice work for average welding conditions. Welding machines should at least be capable of giving plenty of practice with $^3/_{16}$-in. electrodes. In cases where students are being especially trained for employment where larger electrodes are used, the school should have welding machines of sufficient capacity to give this practice. It is rarely necessary for a school to give training in the making of thick multiple layer or multiple bead welds because it is not likely that a beginner would be started on such important work.

Fixtures and equipment should be provided for making qualification tests in the school, and the experience of making welds for these qualification tests can well be regarded as a vital part of the instruction rather than as an accessory demonstration. In this connection, it is advisable to have a permanent display board showing samples of welds of different degrees of soundness which have been fractured so as to show the nature of the weld metal.

MINIMUM REQUIREMENTS

The AMERICAN WELDING SOCIETY Committee on Minimum Requirements for Instruction of Welding Operators in Trade Schools has developed a proposed Code of Minimum Requirements for the guidance of welding schools and for the guidance of employers in evaluating the instruction methods of schools that teach welding. Although the work on the proposed Code has not been completed, there are some significant features in the preliminary draft (which has been widely circulated in the welding industry for comment and suggestion) and a brief review of its contents will indicate the usefulness of such a Code.

This Code is to be prepared in four sections, as follows:

Part *A*—Arc Welding Steel $^3/_{16}$ to $^3/_4$ in. Thick
Part *B*—Gas Welding Steel Sheet and Tubing
Part *C*—Arc Welding Steel Sheet and Tubing
Part *D*—Gas Welding Steel Plate and Pipe.

Part *A* consists of two principal parts: (1) a mandatory part, all provisions and requirements of which must be fulfilled by any welding course which is to be considered as complying with the Code; and (2) a nonmandatory part, comprising several appendices and presenting suggested material intended to aid welding schools in complying with the mandatory provisions.

In prescribing the tests which the student is required to pass before completing the course, the Code recognizes that differences in natural ability influence the degree of skill which the student is able to attain. Therefore, provision is made whereby a student who has completed the course and is

yet unable to pass the final tests in all positions, is permitted to receive a record card indicating the positions in which he has passed the test.

A course which meets the requirements of the Code is not expected to produce an experienced operator, but rather an operator with enough skill and knowledge so that he will have immediate value to industry as a welding operator on less difficult work and will be able by gaining experience in industry to progress rapidly to work of greater difficulty. The final objective of such a course is to prepare the student to pass the AMERICAN WELDING SOCIETY Standard Qualification Tests for Welding Operators.

Important fundamentals included in the mandatory provisions of the Code are:

Scope and objective.
Qualifications of student.
Qualifications and duties of instructors.
Equipment and facilities of the school.
Length of course and hours of instruction.

Instruction in welding practice requires exercises in making (*a*) bead welds, (*b*) single-pass fillet welds, (*c*) multiple-pass fillet welds and (*d*) groove welds, in the flat, overhead, vertical and horizontal positions. In each of these groups certain check tests are designated to demonstrate whether the student has acquired a satisfactory degree of skill in the techniques covered.

Required subjects for instruction in welding theory are: Safety; Welding Machines; Welding Processes and Welding Terms; Use of Weld Gages; Characteristics of Good Welds; Weld Testing Methods; Inspection of Welds; the Nature of Iron and Steel; Types of Electrodes and Their Uses.

Mandatory provisions of the Code conclude with an exposition of the final tests required of the student, the base material of test specimens, positions of test welds, number of test welds required, welding procedure, test specimens, methods of testing and evaluation of test results.

Evidence of the intention of the Committee to be helpful rather than regulatory is found in the numerous practical recommendations which are embodied in the Code as appendices. These recommendations cover: school equipment, ventilating systems, positioning jigs, designs of testing apparatus, safety rules, description of electrode classifications and their uses, welding exercises, progress chart, record card, bibliography.

The promulgation of this code provides welding schools with a well-defined picture of what is considered to be a satisfactory instruction method. As indicated previously in this chapter, it should be permissible to deviate from some of the details of such a code, in order to make the instruction conform to local employment requirements, provided the quality of the instruction and the general scope of it is not sacrificed. However, the proposed Code is quantitative in sufficient detail so that the employer can use it to advantage in checking the operations of schools which seek to obtain employment for their graduates. To the welding schools, both public and private, it answers the question as to what the welding industry expects of them, and furnishes numerous valuable and highly practical recommendations.

A COOPERATIVE PROGRAM OF TRAINING

Close cooperation between industry and the schools, both public and private, has been emphasized throughout the foregoing. Experience can come only through employment and work on the job; industry must recognize this fact and in any period in which a shortage of experienced operators exists, accept the partly or school-trained student and through careful supervision, permit him to gain the experience necessary to perform the work assigned. An example of its practical application, both for pre-employment training and in the upgrading of employees, is furnished by the training for welding operators at the plant of a large shipyard on the Atlantic Coast. Certain special circumstances exist in this case which should be given full consideration in evaluating the system and, therefore, the practicability of its application elsewhere:

(*a*) The shipyard is the largest employer of welding operators in the district served by the local vocational school. Since this shipyard offers the principal opportunity for placement of students from private schools, it can bring greater pressure to bear upon their policy than otherwise might obtain.

(*b*) There is no production welding in this plant which can be done by students before qualification to the minimum requirements of the United States Navy, except "tack welding." The welding time in this is so limited that it provides almost no practice or experience for students beyond familiarizing them with equipment and shop conditions.

For a number of years this company operated its own school within the plant. The disadvantages previously enumerated have been so forcibly demonstrated that a policy of close cooperation with local vocational and private schools was inaugurated for both divisions of its training program; namely, (1) pre-employment training and (2) upgrading. In view of the many facilities now available for pre-employment instruction, both public and private, but with principal dependence upon the latter, the shipyard requires a minimum amount of instruction and the ability to pass the tests described below, before employment. The prospective employee is required to obtain this either at the local vocational school or at his own expense at a private school accredited by the shipyard. Before being admitted for test, the applicant is required to present a certificate or letter from the school certifying that he has completed the minimum instruction course outlined by the Yard for tack welding and that, in the opinion of the school, he is ready for the preliminary test, details of which have been made known to all concerned.

Following successful completion of this test, which is given at the plant, the student is offered employment as a "welder-learner." As such, he will perform tack welding on the job during regular working hours but agrees to continue attendance at a welding school designated by the company for a minimum of six hours a week, outside of working hours. Full use is made of the facilities provided by the vocational schools but when these facilities are inadequate for the peak periods of training, learners are sent to private schools at the company's expense. These schools are carefully selected and must meet rigid requirements as to equipment and instructors, and must follow the course of instruction furnished by the shipyard. A traveling inspector spends full time visiting these schools checking on progress of students and maintaining adherence to the terms of the contract.

All instructors must demonstrate their ability to pass all qualification tests required. As a matter of fact, many of the instructors, both full and part-time, at all schools involved are shipyard operators or subforemen, a number of whom have been furloughed to take full-time teaching positions. Complete records are maintained on each welder-learner and the relative efficiency of instruction at various schools and of various instructors is readily determined. The number of school hours per man to qualify for minimum requirements for Navy work is relatively low although the calendar time, due to only six hours per week of steady welding time, may be unduly long. This can be reduced only by the provision of some form of work during the learner's regular working hours which would provide more welding time than in tacking.

After completion of the advanced course in welding black and galvanized steel, all types of joints in all positions using $^3/_{16}$-in. electrode for vertical and overhead and the larger diameters for down-hand work, the learner is given the Navy No. 1 welding test. Passing this test terminates his course of instruction in the outside school and establishes his rating as a third-class welding operator. From this point on, his upgrading and instruction on special materials is accomplished on the job and by a limited amount of school instruction and practice time within the plant. No method has yet been worked out to obtain adequate instruction elsewhere in special processes frequently involving the use of expensive electrodes and materials not available to schools.

An essential feature of the close cooperation between the company and the schools, both public and private, is the provision of suitable scrap, prepared for instruction. All plate scrap in the plant is assigned to the training program and after being cut into suitable sizes for the use of students, is assigned to the various schools in the approximate ratio of their quota of learners. For those men who have nearly completed the course and are preparing for qualification, regulation test plates are provided for practice, although the official tests are given at the company's plant, observed by the Navy or other inspection agency involved.

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CHAPTER 29

STANDARD QUALIFICATION PROCEDURE*

Manual Arc and Gas Welding of Ferrous Materials, Part I—Procedure Qualification, Part II—Operator Qualification, Grouping of Materials, Recommended Forms of Procedure Specifications.

FOREWORD

It is recognized that the quality of arc- and gas-welded joints will be determined by the specific welding procedure used and by the ability of the welding operator to apply that procedure. Predictable results as to the physical properties and soundness of such joints can be secured only by adherence to a procedure of welding that has been thoroughly investigated. It cannot be expected that good results will be obtained, even by careful and painstaking workmen, if poor material, inadequate or worn out equipment are used, or if fundamentally improper methods are pursued. Nor can the purpose of welding be obtained by the mere adoption of a carefully outlined procedure of welding, if the welding operators have not been given a certain degree of training and are not properly supervised to be certain that all essential details of the specific procedure for welding are followed.

In arc and gas welding, the physical properties of the weld metal, such as tensile strength and ductility, will be determined by the particular procedure of welding that is used. The reliability of the welded joint will be determined by the degree to which that weld metal is kept free of foreign materials, such as slag, and by the degree to which it is fused to the base material. Under a fixed procedure of welding these two latter factors are the only ones over which the welding operator has control. It is considered unnecessary, therefore, to test welds of every operator for tensile strength and ductility. It is the belief of the Committee that the first step in welding must be the adoption of a procedure of welding in which all essential variables are fixed within definite limits. The procedure for welding should then be investigated to determine whether it will produce welds with the desired physical properties. The tests required for a welding operator are included in the investigation of a welding procedure because there have been many instances wherein failure to obtain results has been attributed to the inability of the operator when the difficulty lay in the fundamentals of the procedure. Having established that a given procedure is satisfactory, comparatively simple tests, intended primarily to determine the ability of an individual to make a sound weld, may then be used for the qualification of welding operators.

In Part I there is given the method to be pursued in investigating and qualifying a welding procedure, while Part II outlines the method of qualifying welding operators.

There are several variables involved in any procedure of welding, and if predictable results are to be obtained, certain limitations must be placed

* Standard of the AMERICAN WELDING SOCIETY.

upon those variables before the procedure for welding is tested. Having fixed upon these limitations, it is necessary that some tolerance or degree of departure from a given limitation of a variable, as stated in a procedure specification, be recognized as permissible without requiring that a retest of the procedure be made. Such departures from a fixed procedure of welding as might affect the predictable results to be obtained, may be referred to as essential changes. The tests which must be made to determine the effect that a given essential change will have upon the predictable results will depend upon the nature of that change. In some cases a test of the procedure for welding, embodying the change, will be necessary, in other cases a test of the welding operator only will be sufficient, and in still other cases a test of both the new procedure and the individual operators will be required.

A tabulation of the variables and of those changes in variables which are considered to be essential changes, together with the type of investigation necessary—whether of procedure, operator or both—is given in Article 101.

The Committee has given much thought to the need for simplification of the test of a welding operator, and the type of tests outlined herein are designed to ascertain that the operator has a sufficient knowledge of and the skill to apply a procedure of welding under average conditions. For this purpose, a special shape of welding groove, intended to be used only for operator test specimens, has been adopted.

The Committee has also been seeking and now presents a type of operator test specimen for fillet welded joints that may be readily tested in a guided bend test jig, thus providing a test that is not only inexpensive and simple to make, but also one that avoids question of judgment as to the results obtained.

It is the conviction of the Committee that there are so many essential factors involved in the successful application of arc and gas welding, embracing such items as quality of filler metal, adaptability of the welding procedure and equipment, facilities provided for preparing the work, etc., that the manufacturer or contractor alone should be expected to be responsible for the integrity of the finished weld. It should be borne in mind that it is the manufacturer or contractor who is financially responsible for the quality of the welding performed and that in the case of failure thereof the welding operator assumes no share of the financial burden. In these rules, therefore, the entire responsibility for quality of the welding performed will be assumed to lie with the manufacturer or contractor.

The Committee will be pleased to provide any interpretations that may assist in the application of this standard.

GENERAL

These rules are intended to apply only to the manual application of the arc- and gas-welding processes, and to those ferrous metals which in their unwelded condition will meet the requirements of the guided bend test prescribed herein.

Each manufacturer or contractor shall be responsible for the quality of the welding done by his organization and shall conduct tests not only of the welding procedure to determine its suitability to ensure welds which will

meet the required tests, but also of the welding operators to determine their ability to make sound welds under standardized test conditions.

It is assumed that the manufacturer or contractor has an organization familiar with the various welding codes and capable of designing, engineering and supervising welded construction.

Rules for the qualification of a welding procedure are given in Part I. Rules for qualifying operators follow in Part II.

PART I—PROCEDURE QUALIFICATION

101. Limitation of Variables

(*a*) The procedure of welding to be followed in construction shall be established and recorded by the manufacturer or contractor as a Procedure Specification, and in the investigation to qualify this procedure, the Procedure Specification shall be followed. Recommended forms for the Procedure Specification are given in the Appendix. It is not necessary that these exact forms be used, but the information contained therein should be set forth in any alternate form which is adopted.

(*b*) If any changes are made in a procedure, the Procedure Specification shall be revised or amended to show these changes.

The changes set forth in the following schedule shall be considered essential changes and shall require requalification of the procedure or operator or both. Any change marked "P" or "PO" shall require requalification of the procedure; any change marked "PO" or "O" shall require requalification of the operator.

P	1	A change in the specification of base metal to be welded from one "P" Number to another "P" Number. (See Table 5.)*
PO	2	A change in the specification of base metal to be welded from one "O" Number to another "O" Number. (See Table 5.)
PO	3	A change in filler metal from one American Welding Society Specification** to another Specification.
P	4	A change in filler metal from one American Welding Society Classification Number† to another American Welding Society Classification Number.
O	5	A change in filler metal from a bare or lightly coated electrode to a covered electrode, or vice versa, within any given American Welding Society specification for arc welding electrodes.‡

* When any "P" group in Table 5 contains materials having specified minimum tensile strengths higher than the tensile strength obtained in the actual procedure qualification tension test, it may be desirable for governing codes to require procedure qualification using these higher tensile materials before they can be welded in actual construction.

** See American Welding Society filler metal specifications.

† For example: A change from an E6010 to an E6012 or E7010 electrode (Tentative Specifications for Iron and Steel Arc Welding Electrodes); or a change from a G60 to a G45 or G65 welding rod (Tentative Specifications for Iron and Steel Gas Welding Rods).

‡ For example: A change from an E6010 to an E4510 electrode requires requalification of the operator; a change from an E6010 to an E6020 or E6030 electrode *does not* require requalification of the operator (Tentative Specifications for Iron and Steel Arc Welding Electrodes).

P	6	An increase in the diameter of the electrode or welding rod used, over that called for in the Procedure Specification.
P	7	A change of more than 15 per cent above or below the specified mean arc voltage and amperage for each size electrode used.
P	8	For a specified welding groove, a change of more than plus or minus 25 per cent in the specified number of passes. If the area of the groove is increased, it is also permissible to increase the number of passes in proportion to the increased area.
PO	9	A change in the position in which welding is done as defined in Articles 104 and 204.
O	10	In the case of vertical welds, a change from the progression specified for any pass from upward to downward or vice versa.
P	11	A decrease in the preheating temperature.
P	12	A change in the heat-treating temperature range or time range.
P	13	A change in the specified range of sizes of gas-welding tips.
P	14	A change of gas-welding flame from neutral to one with an excess of acetylene or vice versa.
O	15	A change from the "backhand" to the "forehand" method of welding. (Gas or carbon arc welding.)
P	16	A decrease in the number of layers used in gas welding.
P	17	A change in the type of welding groove. (Example, change from a V to a U shape.)
P	18	A change in the shape of any one type of welding groove involving: (1) a decrease in the included angle of the welding groove, or a decrease in the width of the groove; or (2) a decrease in the root opening of a welding groove; or (3) an increase in the root face of a welding groove; or (4) the addition or omission of a backing strip.

102. Types of Tests and Purposes

The types of tests outlined below are to determine the tensile strength, ductility and degree of soundness of welded joints made under a given Procedure Specification. The tests used are as follows:

(*a*) *For Groove Welds*

(1) Reduced-Section Tension Test (for Tensile Strength)
(2) Free-Bend Test (for Ductility)
(3) Root-Bend Test (for Soundness)
(4) Face-Bend Test (for Soundness)
(5) Side-Bend Test (for Soundness)

(*b*) *For Fillet Welds*

(1) Longitudinal or Transverse Shear Test (for Shear Strength)
(2) Free-Bend Test (for Ductility)
(3) Fillet-Weld-Soundness Test (for Soundness)

103. Base Material and Its Preparation

The base material and its preparation for welding shall comply with the

Procedure Specification.* For all types of welded joints the length of the weld and the dimensions of the base material shall be such as to provide sufficient material for the test specimens called for hereinafter.

104. Position of Test Welds

All welds that will be encountered in actual construction, except groove welds in pipe, shall be classified as being (1) Flat, (2) Horizontal, (3) Vertical or (4) Overhead, in accordance with the definitions of welding positions given in Fig. 1 (*a*) and 1 (*b*). Groove welds in pipe shall be classified as (1) Horizontal Rolled, (2) Horizontal Fixed or (3) Vertical, in accordance with the definitions of pipe welding positions given in Fig. 1 (*a*). Each procedure shall be tested in the manner stated below for each position for which it is to be qualified.

(*a*) *Groove Welds in Plate*

In making the tests to qualify groove welds in plate, the test plates shall be welded in the following positions:

(*1*) *Flat Position*—The test plates shall be placed in an approximately horizontal plane and the weld metal deposited from the upper side. (Illustrated in Fig. 21 (*a*).)
(*2*) *Horizontal Position*—The test plates shall be placed in an approximately vertical plane with the welding groove approximately horizontal. (Illustrated in Fig. 21 (*b*).)
(*3*) *Vertical Position*—The test plates shall be placed in an approximately vertical plane with the welding groove approximately vertical. (Illustrated in Fig. 21 (*c*).)
(*4*) *Overhead Position*—The test plates shall be placed in an approximately horizontal plane and the weld metal deposited from the under side. (Illustrated in Fig. 21 (*d*).)

(*b*) *Groove Welds in Pipe*

In making the tests to qualify groove welds in pipe, the pipe shall be welded in the following positions:

(*1*) *Horizontal Rolled*—The pipe shall be placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane and the pipe shall be rolled during welding. (Illustrated in Fig. 21 (*a*).)
(*2*) *Horizontal Fixed*—The pipe shall be placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane and the pipe shall not be rolled or turned during welding. (Illustrated in Fig. 21 (*e*).)
(*3*) *Vertical*—The pipe shall be placed with its axis in an approximately vertical position with the welding groove in an approximately horizontal plane. (Illustrated in Fig. 21 (*b*).)

* To avoid misleading results it is desirable that the base material used in the qualification of a procedure contain amounts of carbon, manganese, chromium, molybdenum and other alloys approaching the maximum quantities of these elements which may be present in the materials that will be welded in actual construction.

(*c*) *Fillet Welds*

In making the tests to qualify fillet welds in plate, the test plates shall be welded in the positions outlined below. (If fillet welds are to be made in pipe, they shall be qualified by tests made in plate unless other tests are specifically provided for by a governing Code.)

(*1*) *Flat Position*—The test plates shall be so placed that each fillet weld is deposited with its axis approximately horizontal and its throat approximately vertical. (See Fig. 2 (*a*).)

(*2*) *Horizontal Position*—The test plates shall be so placed that each fillet weld is deposited on the upper side of the horizontal surface and against the vertical surface. (See Fig. 2 (*b*).)

(*3*) *Vertical Position*—Each fillet weld shall be made vertically. (See Fig. 2 (*c*).)

(*4*) *Overhead Position*—The test plates shall be so placed that each fillet weld is deposited on the under side of the horizontal surface and against the vertical surface. (See Fig. 2 (*d*).)

NOTE: The above arrangement of test plates refers only to the making of the fillet welds. The closing weld between fillet welds in the fillet-weld-soundness test may be made in any position.

105. Number of Test Welds Required

(*a*) *Groove Welds in Plate or Pipe*

For groove welds in material up to and including $^3/_4$ in. thick, one test weld shall be made in material $^3/_8$ in. thick* for each procedure and position to be used in construction, except that if the construction involves welding of material over $^3/_4$ in. thick, a test weld shall be made in material of the maximum thickness* to be used in construction for each procedure and position, but which need not exceed 1 in.* If a test is made in the maximum or 1 in. thickness, no test need be made in the $^3/_8$ in. thickness. In the case of pipe, the nominal diameter of the pipe used for the test weld shall not be less than 6 in.

(*b*) *Fillet Welds*

For fillet welds two longitudinal or two transverse shear test welds shall be made for each procedure and position to be used in construction. For each type of test weld, one shall be made with the maximum size single-pass fillet weld and one with the minimum size multiple-pass fillet weld that will be used in construction. In addition, one test weld for the free-bend and fillet-weld-soundness tests shall be made with the maximum size single-pass fillet weld (not over $^3/_8$ in.) that will be used in construction, for each procedure and position to be used in construction.

106. Welding Procedure

The welding procedure shall comply in all respects with the Procedure Specification.

* In the case of pipe, the wall thickness may vary + or $-12^1/_2$ per cent from that indicated.

107. Test Specimens—Number, Type and Preparation

(a) *Groove Welds*

For groove welds in plate the method of preparing the specimens shall be in accordance with the figures referred to in Table 1 and the number of tests required shall be as given in the table. The test specimens shall be removed in the order given in Figs. 10 and 11.

For groove welds in pipe the method of preparing the specimens shall be in accordance with the figures referred to in Table 2 and the number of tests required shall be as given in the table. The test specimens shall be removed in the order given in Figs. 15 and 16.

TABLE 1—PROCEDURE QUALIFICATION TESTS FOR GROOVE WELDS IN PLATE

Maximum Thickness to Be Welded in Construction	Test Plate Thickness	Number and Type of Tests Required				
		Reduced-Section Tension. (See Fig. 6)	Free-Bend. (See Fig. 7)	Root-Bend. (See Fig. 8)	Face-Bend. (See Fig. 8)	Side-Bend. (See Fig. 9)
Up to and including 3/4 in.	3/8 in.	2	2	2	2	..
Over 3/4 in.	Maximum, but need not exceed 1 in.	2	2	..	..	4

TABLE 2—PROCEDURE QUALIFICATION TESTS FOR GROOVE WELD IN PIPE

Maximum Thickness to Be Welded in Construction	Test Pipe Wall Thickness	Number and Type of Tests Required				
		Reduced-Section Tension. (See Fig. 12)	Free-Bend. (See Fig. 13)	Root-Bend. (See Fig. 14)	Face-Bend. (See Fig. 14)	Side-Bend. (See Fig. 9)
Up to and including 3/4 in.	3/8 in.	2	2	2	2	..
Over 3/4 in.	Maximum, but need not exceed 1 in.	2	2	..	..	4

(b) *Fillet Welds*

The longitudinal shear test specimens shall be welded as shown in Fig. 3 and prepared for testing as shown in Fig. 17. The transverse shear test specimens shall be made as shown in Fig. 4.

The test weld for the free-bend and soundness tests shall be made as shown in Fig. 5. From the test weld there shall be taken two free-bend test specimens, which shall be prepared for testing as shown in Fig. 7, and two fillet-weld-soundness test specimens as shown in Fig. 20.

108. Method of Testing Specimens

(*a*) *Reduced-Section Tension Specimens*

Before testing, the least width and corresponding thickness of the reduced-section shall be measured in inches. The specimen shall be ruptured under tensile load and the maximum load in pounds shall be determined. The cross-sectional area shall be obtained as follows: cross-sectional area = width × thickness. The tensile strength in pounds per sq. in. shall be obtained by dividing the maximum load by the cross-sectional area.

(*b*) *Free-Bend Test Specimens*

The gage lines indicated in Fig. 7 shall be lightly scribed on the face of the weld. The gage length (distance between gage lines) shall be approximately $^1/_8$ in. less than the width of the face of the weld, and shall be measured in inches to the nearest 0.01 in.

Each specimen may be bent initially by the use of a fixture complying with the requirements of Fig. 18. The surface of the specimen containing the gage lines shall be directed toward the supports. The weld shall be at midspan of both the supports and the loading block. Alternatively, the initial bend may be made by holding each specimen in the jaws of a vise with one-third the length of the specimen projecting from the jaws, then bending the specimen away from the gage lines through an angle of from 30 to 45° by blows of a hammer. The other end of the specimen shall be bent in the same way. In order that the final bend shall be centered on the weld, the initial bends shall be symmetrical with respect to the weld, and both ends shall be bent through the same angle. The initial bend may also be started at the weld by placing the specimen in the guided-bend test jig shown in Fig. 19.

Compressive forces shall be applied to the ends of the specimen, continuously decreasing the distance between the ends. (Any convenient means such as a vise or a testing machine may be used for the final bend.) When a crack or other open defect exceeding $^1/_{16}$ in.* in any direction appears on the convex face of the specimen, the load shall immediately be removed. If no crack appears, the specimen shall be bent double. Cracks occurring on the corners of the specimen during testing shall not be considered.

The elongation shall be determined by measuring the minimum distance between the gage lines, along the convex surface of the weld, to the nearest 0.01 in. and subtracting the initial gage length. The per cent elongation shall be obtained by dividing the elongation by the initial gage length and multiplying by 100.

(*c*) *Root-, Face-, Side-Bend and Fillet-Weld-Soundness Specimens*

Each specimen shall be bent in a jig having the contour shown in Fig. 19, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving the male member with relation to the female member.

The specimen shall be placed on the female member of the jig with the weld at midspan. Face-bend specimens shall be placed with the face of the weld directed toward the gap; root-bend and fillet-weld-soundness specimens shall be placed with the root of the weld directed toward the gap; side-bend specimens shall be placed with that side showing the greater

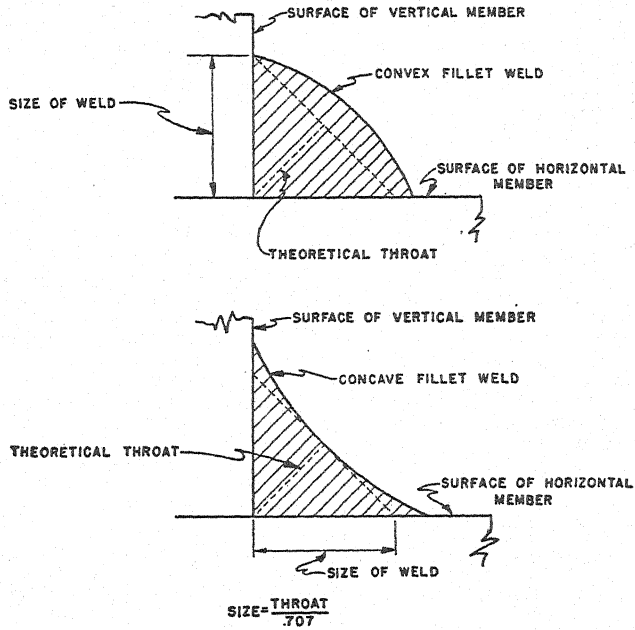
* See Note I on page 1006.

defects, if any, directed toward the gap. The two members of the jig shall be forced together until the curvature of the specimen is such that a $^1/_{32}$ in. diameter wire cannot be passed between the curved portion of the male member and the specimen. The specimen shall then be removed from the jig.

(*d*) *Longitudinal and Transverse Shear Test Specimens*

Before testing, the length of the individual welds shall be measured in inches and if any weld varies by more than $^1/_{16}$ in. from the length specified in Figs. 4 and 17, then the length of each weld and its location shall be recorded. The average size of the fillet welds shall also be recorded. The specimen shall be ruptured under tensile load and the maximum load in pounds shall be determined. The shearing strength of the welds in pounds per linear inch shall be obtained by dividing the maximum force by the sum of the lengths of the welds which ruptured. The shearing strength of the welds in pounds per sq. in. shall be obtained by dividing the shearing strength in pounds per linear inch by the average theoretical throat dimension of the welds in inches.

NOTE: The size and theoretical throat dimension of a fillet weld shall be defined as illustrated in the sketch below. The size of a fillet weld is the leg length of the largest inscribed isosceles right triangle. The theoretical throat dimension may be obtained by multiplying the size of the fillet weld by 0.707.



109. Test Results Required

The requirements for the test results shall be as follows:

(*a*) *Reduced-Section Tension Test*

The tensile strength shall be not less than 100 per cent of the minimum of the specified tensile range of the base material used. (See Notes I and III.)

(*b*) *Free-Bend Test*

The elongation shall be not less than 30 per cent for stress-relieved welds nor less than 25 per cent for non-stress-relieved welds. (See Notes I and III.)

(*c*) *Root-, Face-, Side-Bend and Fillet-Weld-Soundness Tests*

The convex surface of the specimen shall be examined for the appearance of cracks or other open defects Any specimen in which a crack or other open defect is present after the bending, exceeding $^1/_8$ in. measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered. (See Notes I and III.)

(*d*) *Longitudinal or Transverse Shear Test*

For the longitudinal shear test specimen the shearing strength of the welds in pounds per square inch shall be not less than $^2/_3$ of the minimum of the specified tensile range of the base material. For the transverse shear test specimen the shearing strength of the welds in pounds per sq. in. shall be not less than $^7/_8$ of the minimum of the specified tensile range of the base material. (See Notes I, II and III.)

NOTE I: These values as set forth shall apply where no Code is in effect, or where an agreement to use other values has not been made between the purchaser and vendor.

NOTE II: These values are applicable only to low carbon, non-alloy steels. For other materials, the values shall be a matter of agreement between the purchaser and vendor.

NOTE III: The test results specified are not likely to be attained with the metal arc process when using bare or lightly coated electrodes. For such processes it is recommended that the governing Code adopt the following requirements for the test results:

a. Reduced-Section Tension Test—The tensile strength shall be not less than 85 per cent of the minimum of the specified tensile range of the base material used.

b. Free-Bend Test—The elongation shall be not less than 10 per cent.

c. Root-, Face-, Side-Bend and Fillet-Weld-Soundness Tests—The specimen shall be considered as having passed if (1) no crack or other open defect exceeding $^1/_8$ in. measured in any direction is present in the weld metal or between the weld and base material after the bending, or (2) the specimen has cracked or fractured and the fractured surface shows complete penetration through the entire thickness of the weld, and absence of slag inclusions and porosity to the extent that there are no gas pockets or slag inclusions exceeding $^1/_{16}$ in. in greatest dimension and the sum of the greatest dimension of all such defects in any square inch of weld metal area does not exceed $^3/_8$ in. (If necessary, the specimen shall be broken apart to permit examination of the fracture.)

d. Longitudinal or Transverse Shear Test—For the longitudinal shear test specimen the shearing strength of the welds in pounds per square inch shall be not less than $^2/_3$ of the minimum of the specified tensile range of the base material. For the transverse shear test specimen the shearing strength of the welds in pounds per sq. in. shall be not less than $^7/_8$ of the minimum of the specified tensile range of the base material.

110. Records

Records of the test results shall be kept by the manufacturer or contractor and shall be available to those authorized to examine them.

PART II—OPERATOR QUALIFICATION

201. Limitation of Variables

For the qualification of an operator the following rules shall apply. If certain changes are made in a Procedure Specification, operator requalification may be required in accordance with Article 101 (*b*).

202. Types of Tests Required

The qualification tests described herein are specially devised tests to determine the operator's ability to produce sound welds, and may or may not conform in every detail to the requirements of the Procedure Specification. It is not intended that the practices required in the qualification tests shall be used as a guide for welding during actual construction. The latter shall be performed in accordance with the requirements of the Procedure Specification.

The tests used for operator qualification are as follows:

(*a*) *For Groove Welds*

(1) Root-Bend Test
(2) Face-Bend Test
(3) Side-Bend Test

(*b*) *For Fillet Welds*

Fillet-Weld-Soundness Test

203. Base Material and Its Preparation

(*a*) The base material shall comply with the specification for one of the materials listed in the Procedure Specification. For all types of welded joints the length of the weld and the dimensions of the base material shall be such as to provide sufficient material for the test specimens called for hereinafter.

(*b*) For groove welds in plate or pipe where the thickness of the material for the tests as specified in Article 205 (*a*) is $^3/_8$ in., the preparation of the base material for welding shall be for a single-V groove butt joint meeting the requirements of Fig. 22, except that in the case of oxyacetylene welding the joint preparation may be in accordance with Fig. 24.

(*c*) For groove welds in plate or pipe where the thickness of the material as specified in Article 205 (*a*) exceeds $^3/_8$ in., the preparation of the base material for welding shall be for a single-V groove butt joint meeting the requirements of Fig. 23, except that in the case of oxyacetylene welding the joint preparation may be in accordance with Fig. 25.

(*d*) For fillet welds the preparation of the base material for welding shall be as shown in Fig. 26. Pipe with a nominal diameter of not less than 6 in. may be used in lieu of plate.

204. Position of Test Welds

(*a*) *Groove Welds*

For the purpose of determining the ability of an operator to make groove welds in various positions in plate or pipe the following positions for test are required.

Test Position 1G

Plates placed in an approximately horizontal plane and the weld metal deposited from the upper side, or a pipe placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane, the pipe being rolled while the weld is deposited within the top quadrant and from the outside of the pipe. (See Fig. 21 (*a*).) This test made either in plate or pipe will qualify the operator for flat position welds in plate and for pipe in the horizontal rolled position. (See Fig. 1 (*a*).)

Test Position 2G

Plates placed in an approximately vertical plane with the welding groove in an approximately horizontal plane, or a pipe placed with its axis in an approximately vertical plane with the welding groove in an approximately horizontal plane. (See Fig. 21 (*b*).) This test made either in plate or pipe will qualify the operator for flat and horizontal welds in plate and for pipe in the horizontal rolled and vertical fixed positions. (See Fig. 1 (*a*).)

Test Position 3G

Plates placed in an approximately vertical plane with the welding groove approximately vertical. (See Fig. 21 (*c*).) This test will qualify the operator for flat and vertical welds in plate and for pipe in the horizontal rolled position. (See Fig. 1 (*a*).)

Test Position 4G

Plates placed in an approximately horizontal plane and the weld metal deposited from the under side. (See Fig. 21 (*d*).) This test will qualify the operator for flat, and overhead welds in plate and for pipe in the horizontal rolled position.

Test Position 5G

A pipe or plate box placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane. The pipe or box shall not be rolled or turned during welding, thus requiring the operator to deposit weld metal from the flat, vertical and overhead positions. (See Fig. 21 (*e*).) This test made either in pipe or a plate box will qualify the operator for welds made in plate in the flat, vertical and overhead positions, and in pipe in the horizontal rolled and horizontal fixed positions. (See Fig. 1 (*a*).)

If a welding operator is tested in Position 2G he need not be tested in Position 1G. If a welding operator is tested in Position 3G he need not be tested in Position 1G. If a welding operator is tested in Position 4G he need not be tested in Position 1G. If a welding operator is tested in Position 5G he need not be tested in Position 1G, 3G or 4G.

(*b*) *Fillet Welds*

For the purpose of determining the ability of an operator to make fillet welds in various positions the following positions for test are required:

Test Position 1F

Plates placed in such position that each weld is deposited with its axis approximately horizontal and with its throat approximately vertical. (See Fig. 27 (*a*).) This test will qualify the operator for flat fillet welds. (See Fig. 1 (*b*).)

Test Position 2F

Plates or pipe placed in such position that each weld is deposited on the upper side of the horizontal surface and against the vertical surface. (See Fig. 27 (*b*).) This test, made either in plate or pipe, will qualify the operator for flat and horizontal fillet welds. (See Fig. 1 (*b*).)

Test Position 3F

Plates or pipe placed in such position that each weld is made vertically. (See Fig. 27 (*c*).) This test, made either in plate or pipe, will qualify the operator for flat, horizontal and vertical fillet welds. (See Fig. 1 (*b*).)

Test Position 4F

Plates or pipe placed in such position that each weld is deposited on the under side of the horizontal surface and against the vertical surface. (See Fig. 27 (*d*).) This test, made either in plate or pipe, will qualify the operator for flat, horizontal and overhead fillet welds. (See Fig. 1 (*b*).)

NOTE: The above arrangement of test plates or pipe refers only to the making of the fillet weld. The closing weld between fillet welds in the fillet-weld-soundness test may be made in any position. See Fig. 27 (*e*).

If a welding operator is tested in Position 2F he need not be tested in Position 1F. If a welding operator is tested in Position 3F he need not be tested in Position 1F or 2F. If a welding operator is tested in Position 4F he need not be tested in Position 1F or 2F.

205. Number of Test Welds Required

(*a*) *Groove Welds in Plate and Pipe*

For groove welds in material up to and including $^3/_4$ in. thick* one test weld as shown in Fig. 22 (Fig. 24 may be used for oxyacetylene welding) shall be made in material $^3/_8$ in. thick for each position for which the operator is to be qualified as defined by Article 204 (*a*), except that if the construction involves welding of material over $^3/_4$ in. thick* one test weld as shown in Fig. 23 (Fig. 25 may be used for oxyacetylene welding) shall be made for each such position in material of the maximum thickness to be used in construction, but the thickness of the material for the test weld need

* Whereas reference has been made above to the test welds being made in material of a given thickness, it is the intent of these rules that if an operator is qualified to weld in a single groove of a given depth, he is also considered as being qualified for welding double-groove butt joints wherein the depth of the groove from either side does not exceed the depth of the single groove for which he has been qualified.

not exceed 1 in. If a test weld is made in the maximum or 1-in. thickness, no test weld need be made in the $^3/_8$-in. thickness. In the case of pipe, the nominal diameter of the pipe used for the test weld shall not be less than 6 in.

(*b*) *Fillet Welds*

For fillet welds one test weld as shown in Fig. 26 shall be made for each position for which the operator is to be qualified, as defined by Article 204 (*b*).

206. Welding Procedure

The operator shall follow the welding procedure specified by the Procedure Specification except that if the form of the test joint differs from the forms of joint as shown in the Procedure Specification to such a degree that it is necessary, in welding the test joint, to change the electrode or welding rod diameters or the number and arrangement of passes from that called for in the Procedure Specification, such changes shall be permissible.

207. Test Specimens—Number, Type and Preparation

(*a*) *Groove Welds*

For groove welds in plate the method of preparing the specimens shall be in accordance with the figures referred to in Table 3 and the number of tests required shall be as given in the table.

For groove welds in pipe the method of preparing the specimens shall be in accordance with the figures referred to in Table 4 and the number of tests required shall be as given in the table.

If the test weld is made in pipe in Position 1G or 2G, the specimens shall be removed approximately 90° from each other. If the test weld is made in Position 5G, using either a pipe or a plate box, a specimen shall be removed from the top, the bottom and each of the two sides of the test weld; and, if the weld is made in $^3/_8$-in.-thick material, the specimen from the top and one side shall be tested with the face of the weld in tension, and the specimen from the bottom and from the other side shall be tested with the root of the weld in tension.

(*b*) *Fillet Welds*

Two test specimens shall be removed from each test weld and prepared for testing as shown in Fig. 20.

208. Method of Testing Specimens

(*a*) *Root-, Face-, Side-Bend and Fillet-Weld-Soundness Specimens*

Each specimen shall be bent in a jig substantially in accordance with Fig. 19. Any convenient means may be used for moving the male member with relation to the female member.

The specimen shall be placed on the female member of the jig with the weld at midspan. Face-bend specimens shall be placed with the face of the weld directed toward the gap; root-bend and fillet-weld-soundness specimens shall be placed with the root of the weld directed toward the gap; side-bend specimens shall be placed with that side showing the greater defects, if any, directed toward the gap. The two members of the jig shall be forced together until the curvature of the specimen is such that a $^1/_{32}$-

TABLE 3—OPERATOR QUALIFICATION TESTS FOR GROOVE WELDS IN PLATE

Maximum Thickness for Which Operator Is to Be Qualified	Thickness of Material for Test Weld	Number and Type of Tests Required		
		Root-Bend. (See Fig. 8)	Face-Bend. (See Fig. 8)	Side-Bend. (See Fig. 9)
Up to and including 3/4 in.	3/8 in.	1	1	..
Over 3/4 in.	Maximum, but need not exceed 1 in.	..	..	2

TABLE 4—OPERATOR QUALIFICATION TESTS FOR GROOVE WELDS IN PIPE

Maximum Thickness for Which Operator Is to Be Qualified	Thickness of Material for Test Weld	Number and Type of Tests Required		
		Root-Bend. (See Fig. 14)	Face-Bend. (See Fig. 14)	Side-Bend. (See Fig. 9)
Up to and including 3/4 in.	3/8 in.	2	2	..
Over 3/4 in.	Maximum, but need not exceed 1 in.	..	..	4

in. diameter wire cannot be passed between the curved portion of the male member and the specimen. The specimen shall then be removed from the jig.

209. Test Results Required

(*a*) *Root-, Face-, Side-Bend and Fillet-Weld-Soundness Tests*

The convex surface of the specimen shall be examined for the appearance of cracks or other open defects. Any specimen in which a crack or other open defect is present after the bending, exceeding 1/8 in. measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered. (See Notes I and II.)

NOTE I: These values as set forth shall apply where no Code is in effect, or where an agreement to use other values has not been made between the purchaser and vendor.

NOTE II: The test results specified are not likely to be attained with the metal arc process when using bare or lightly coated electrodes. For such processes it is recommended that the governing Code adopt the following requirements for the test results:

The specimen shall be considered as having passed if (1) no crack or other open defect exceeding 1/8 in. measured in any direction is present in the weld metal or between the weld and base material after the bending, or (2) the specimen has cracked or fractured and the fractured surface shows complete penetration through the entire thickness of the weld, and absence of slag inclusions and porosity to the extent that there are no gas pockets or slag inclusions exceeding 1/16 in. in greatest dimension and the sum of the greatest dimension of all such defects in any square inch of weld metal area does not exceed 3/8 in. (If necessary, the specimen shall be broken apart to permit examination of the fracture.)

210. Retests

In case an operator fails to meet the requirements of one or more test welds a retest may be allowed under the following conditions:

(*a*) An immediate retest may be made which shall consist of two test

welds of each type on which he failed, all of which shall meet all the requirements specified for such welds.

(*b*) A retest may be made provided there is evidence that the operator has had further training or practice. In this case a complete retest shall be made.

211. Period of Effectiveness

The operator qualification tests herein specified shall be considered as remaining in effect indefinitely unless (1) the welding operator is not engaged in a given process of welding (i.e., arc or gas) for a period of three months or more;* or unless (2) there is some specific reason to question an operator's ability. In case (1) above the requalification test need be made only in the $^3/_8$ in. thickness.

212. Records

Copies of the record for each qualified welding operator shall be kept by the manufacturer or contractor, and shall be available to those authorized to examine them.

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* The intent of this statement is as follows:

An operator who has been qualified for metal arc welding under any given Procedure Specification is not required to requalify for that Procedure unless he has done no metal arc welding for a period of three months or more. In a similar manner the qualification of an operator for gas welding or for carbon arc welding is not considered as having expired unless he has done no gas welding or carbon arc welding, as the case may be, for a period of three months or more.

PERSONNEL OF COMMITTEE ON STANDARD QUALIFICATION PROCEDURE

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C. W. OBERT, ...The Linde Air Products Company
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W. W. SCHMIDT.....Rock Island Arsenal

TABLE 5—GROUPING OF MATERIALS FOR PROCEDURE AND OPERATOR QUALIFICATION*

"P" Number 1—"O" Number 1

Materials in this group shall not have a carbon content exceeding 0.30 per cent, a manganese content exceeding 1.10 per cent, or a silicon content exceeding 0.50 per cent, as determined by ladle analysis. In addition, the carbon content by percentage shall not exceed the value $0.55 - \left(\frac{Mn + Si}{4}\right)$, where Mn is the percentage of manganese and Si is the percentage of silicon.

A. S. T. M. Spec. No.		Name
A-7		Steel for Bridges and Buildings
A-10		Mild Steel Plates
A-30		Boiler and Firebox Steel for Locomotives
A-53		Welded and Seamless Steel Pipe
A-70		Carbon-Steel Plates for Stationary Boilers, etc.
A-78		Low Tensile Strength Carbon Steel Plates of Structural Quality for Welding
A-83		Lap-Welded and Seamless Steel and Lap-Welded Iron Boiler Tubes
A-87	Grade A1	Carbon-Steel and Alloy-Steel Castings for Railroads
	Grade A2	Carbon-Steel and Alloy-Steel Castings for Railroads
A-89		Low Tensile Strength Carbon-Steel Plates of Flange and Firebox Quality
A-105		Forged or Rolled Steel Pipe Flanges for High-Temperature Service
A-106	Grade A	Lap-Welded and Seamless Steel Pipe for High-Temperature Service
	Grade OH	Lap-Welded and Seamless Steel Pipe for High-Temperature Service
A-107	Grade 1	Commercial Quality Hot-Rolled Bar Steels
	Grade 2	Commercial Quality Hot-Rolled Bar Steels
	Grade 3	Commercial Quality Hot-Rolled Bar Steels
	Grade 4	Commercial Quality Hot-Rolled Bar Steels
	Grade 5	Commercial Quality Hot-Rolled Bar Steels
	Grade 17	Commercial Quality Hot-Rolled Bar Steels
A-113		Structural Steel for Locomotives and Cars
A-120		Black Welded and Seamless Steel Pipe, etc. (Galvanized pipe not included)
A-129		Open-Hearth Iron Plates of Flange Quality
A-131		Structural Steel for Ships
A-134		Electric-Fusion-Welded Steel Pipe (Size 30 in. and over)
A-135		Electric-Resistance-Welded Steel Pipe
A-136		Forge-Welded Steel Pipe
A-139		Electric-Fusion-Welded Steel Pipe (8 in. to but not including 30 in. diam.)
A-155		Electric-Fusion-Welded Steel Pipe for High-Temperature and High-Pressure Service
A-178	Grade A	Electric-Resistance-Welded Steel and Open-Hearth Iron Boiler Tubes
	Grade B	Electric-Resistance-Welded Steel and Open-Hearth Iron Boiler Tubes
A-181		Forged or Rolled Steel Pipe Flanges for General Service
A-192		Seamless Steel Boiler Tubes for High-Pressure Service
A-201		Carbon-Silicon Steel Plates of Ordinary Tensile Ranges

* Steels not included in the table require separate procedure and operator qualification except in the case of the so-called low-alloy, high-strength steels. In the latter group of steels separate procedure qualification is required for each change in brand or analysis but "O" Number 1 applies in all cases.

"P" Number 1—"O" Number 1—(*Continued*)

A-215-39T	Grade N-1-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade A-1-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade A-2-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade A-3-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
A-216-40T	Grade WCA	Carbon-Steel Castings Suitable for Fusion Welding, etc. (to 850° F.)
A-235-40T	Grade A	Carbon-Steel Forgings for General Industrial Use
	Grade B	Carbon-Steel Forgings for General Industrial Use
	Grade C	Carbon-Steel Forgings for General Industrial Use
A-236-40T	Grade A	Carbon-Steel Forgings for Locomotives and Cars

"P" Number 2—"O" Number 1

A-42	Wrought-Iron Plates
A-72	Welded Wrought-Iron Pipe
A-73	Wrought-Iron Rolled or Forged Blooms and Forgings
A-162	Uncoated Wrought-Iron Sheets
A-207	Rolled Wrought-Iron Shapes and Bars

"P" Number 3—"O" Number 1

Materials in this group shall not have a carbon content exceeding 0.35 per cent, a manganese content exceeding 1.50 per cent, or a silicon content exceeding 0.50 per cent, as determined by ladle analysis. In addition, the carbon content by percentage shall not exceed the value $0.65 - \left(\frac{Mn + Si}{4}\right)$, where Mn is the percentage of manganese and Si is the percentage of silicon.

(Experience has indicated that it is advisable to preheat up to 350° F. when welding the materials included in this group.)

A-7		Steel for Bridges and Buildings
A-30		Boiler and Firebox Steel for Locomotives
A-70		Carbon-Steel Plates for Stationary Boilers, etc.
A-87	Grade B	Carbon-Steel and Alloy-Steel Castings for Railroads
A-95		Carbon-Steel Castings for Valves, Flanges and Fittings for High-Temperature Service
A-105		Forged or Rolled Steel Pipe Flanges for High-Temperature Service
A-106	Grade B	Lap-Welded and Seamless Steel Pipe for High-Temperature Service
A-107	Grade 6	Commercial Quality Hot-Rolled Bar Steels
	Grade 7	Commercial Quality Hot-Rolled Bar Steels
A 131		Structural Steel for Ships
A-178	Grade C	Electric-Resistance-Welded Steel and Open-Hearth Iron Boiler Tubes
A-181		Forged and Rolled Steel Pipe Flanges for General Service
A-201		Carbon-Silicon Steel Plates of Ordinary Tensile Ranges, etc.
A-210		Medium-Carbon Seamless Steel Boiler and Superheater Tubes
A-212		High-Tensile Strength Carbon-Silicon Steel Plates, etc.
A-215-39T	Grade N-2-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade BW	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade B-1-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade B-2-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
A-216-40T	Grade WCB	Carbon-Steel Castings Suitable for Fusion Welding, etc. (to 850° F.)
A-235-40T	Grade C1	Carbon-Steel Forgings for General Industrial Use
	Grade D	Carbon-Steel Forgings for General Industrial Use
	Grade E	Carbon-Steel Forgings for General Industrial Use
A-236-40T	Grade B	Carbon-Steel Forgings for Locomotives and Cars
	Grade C	Carbon-Steel Forgings for Locomotives and Cars
	Grade D	Carbon-Steel Forgings for Locomotives and Cars

"P" Number 4—"O" Number 1

The carbon content by ladle analysis shall not exceed 0.28 per cent.

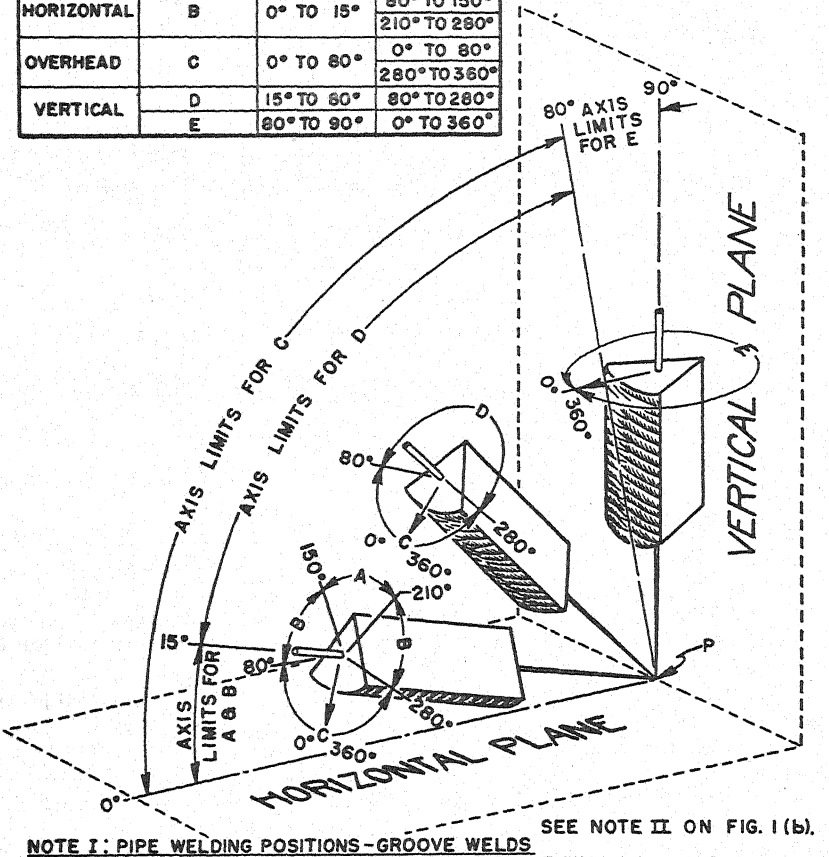
A-182	Grade F1	Forged or Rolled Alloy-Steel Pipe Flanges, etc. (from 750–1100° F.)
A-202	Grade A	Cr-Mn-Si Alloy-Steel Plates for Boilers, etc.
A-203	Grade A	Low-Carbon Nickel-Steel Plates for Boilers, etc.
	Grade B	Low-Carbon Nickel-Steel Plates for Boilers, etc.
A-204	Grade A	Molybdenum-Steel Plates for Boilers, etc.
	Grade B	Molybdenum-Steel Plates for Boilers, etc.
	Grade C	Molybdenum-Steel Plates for Boilers, etc.
A-206-40T		Seamless Carbon-Molybdenum Alloy-Steel Pipe for Service at Temperatures of 750–1000° F.
A-209-40T		Seamless Carbon-Molybdenum Alloy-Steel Boiler and Superheater Tubes
A-217	Grade WC1	Alloy-Steel Castings Suitable for Fusion Welding, etc. (750–1100° F.)
	Grade WC2	Alloy-Steel Castings Suitable for Fusion Welding, etc. (750–1100° F.)
A-225		Manganese-Vanadium Steel Plates for Boilers, etc.

PERSONNEL OF SUB-COMMITTEE ON GROUPING OF MATERIALS FOR PROCEDURE AND OPERATOR QUALIFICATION

C. H. JENNINGS, *Chairman*.....Westinghouse Electric & Mfg. Company
L. C. BIBBER.....Carnegie-Illinois Steel Corporation
A. G. BISSELL.....Bureau of Ships, Navy Department
J. H. DEPPELER.....Metal & Thermit Corporation
W. D. HALSEY.....The Hartford Steam Boiler Inspection & Insurance Co.
N. L. MOCHEL.....Westinghouse Electric & Mfg. Company
H. W. PIERCE.....New York Shipbuilding Corp.
J. F. RANDALL.....Combustion Engineering Company
CHARLES SCHENCK.....Bethlehem Steel Company
W. G. THEISINGER.....Lukens Steel Company

TABULATION OF POSITIONS OF GROOVE WELDS

POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	80° TO 150°
			210° TO 280°
OVERHEAD	C	0° TO 80°	0° TO 80°
			280° TO 360°
VERTICAL	D	15° TO 80°	80° TO 280°
	E	80° TO 90°	0° TO 360°



SEE NOTE II ON FIG. 1 (b).

NOTE I: PIPE WELDING POSITIONS - GROOVE WELDS

FOR GROOVE WELDS IN PIPE THE FOLLOWING DEFINITIONS SHALL APPLY.

HORIZONTAL FIXED POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 30° FROM THE HORIZONTAL PLANE AND THE PIPE IS NOT ROTATED DURING WELDING.

HORIZONTAL ROLLED POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 30° FROM THE HORIZONTAL PLANE, THE PIPE IS ROTATED DURING WELDING, AND THE WELD METAL IS DEPOSITED WITHIN AN ARC NOT TO EXCEED 15° ON EITHER SIDE OF A VERTICAL PLANE PASSING THROUGH THE AXIS OF THE PIPE.

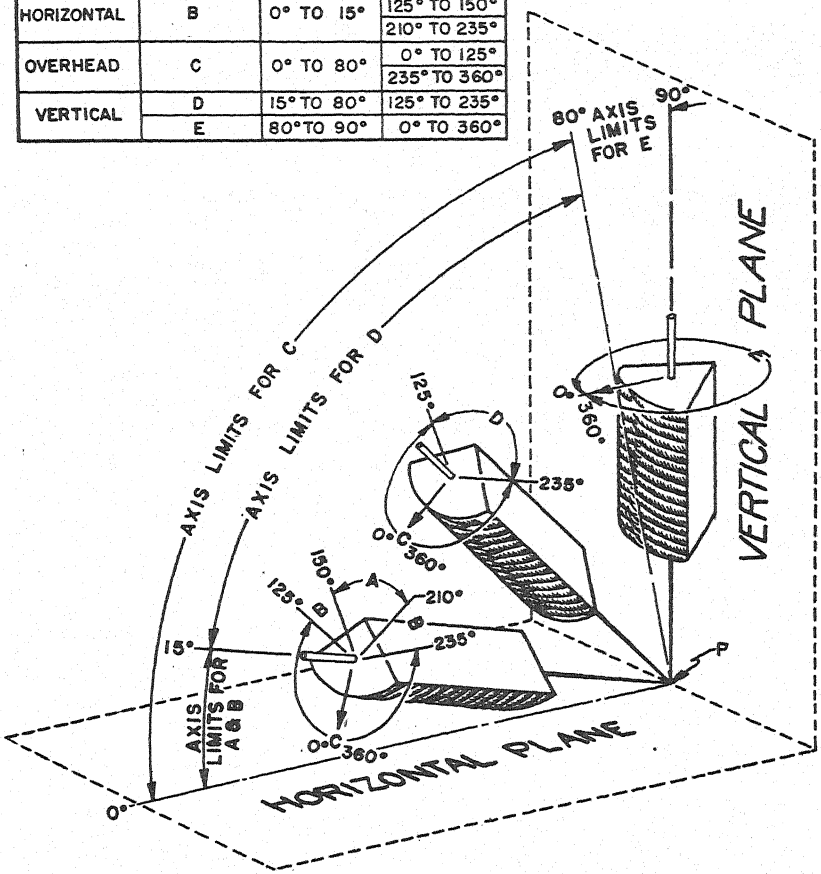
VERTICAL POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 10° FROM THE VERTICAL POSITION (THE PIPE MAY OR MAY NOT BE ROTATED DURING WELDING.)*

*POSITIONS IN WHICH THE AXIS OF THE PIPE DEVIATES BY MORE THAN 10° AND LESS THAN 60° FROM THE VERTICAL SHALL BE CONSIDERED INTERMEDIATE, AND SHALL REQUIRE THE PROCEDURE AND OPERATOR TO BE QUALIFIED IN BOTH THE HORIZONTAL FIXED AND THE VERTICAL POSITIONS.

POSITIONS OF GROOVE WELDS
FIGURE 1(a)

TABULATION OF POSITIONS OF FILLET WELDS

POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	125° TO 150°
			210° TO 235°
OVERHEAD	C	0° TO 80°	0° TO 125°
			235° TO 360°
VERTICAL	D	15° TO 80°	125° TO 235°
	E	80° TO 90°	0° TO 360°



NOTE II:

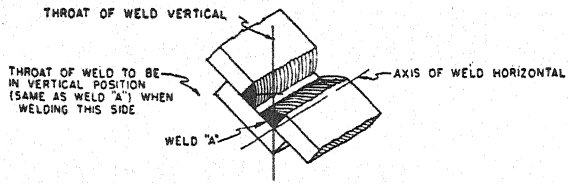
THE HORIZONTAL REFERENCE PLANE IS TAKEN TO LIE ALWAYS BELOW THE WELD UNDER CONSIDERATION.

INCLINATION OF AXIS IS MEASURED FROM THE HORIZONTAL REFERENCE PLANE TOWARD THE VERTICAL.

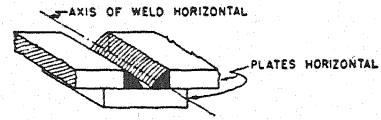
ANGLE OF ROTATION OF FACE IS MEASURED FROM A LINE PERPENDICULAR TO THE AXIS OF THE WELD AND LYING IN A VERTICAL PLANE CONTAINING THIS AXIS. THE REFERENCE POSITION (0°) OF ROTATION OF THE FACE INVARIABLY POINTS IN THE DIRECTION OPPOSITE TO THAT IN WHICH THE AXIS ANGLE INCREASES. THE ANGLE OF ROTATION OF THE FACE OF WELD IS MEASURED IN A CLOCKWISE DIRECTION FROM THIS REFERENCE POSITION (0°) WHEN LOOKING AT POINT P.

POSITIONS OF FILLET WELDS

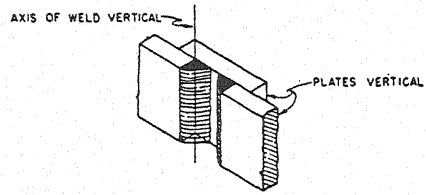
FIGURE 1 (b)



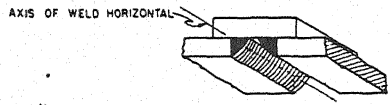
(a) POSITION OF TEST PLATES FOR FLAT FILLET WELD



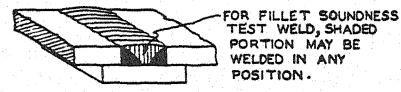
(b) POSITION OF TEST PLATES FOR HORIZONTAL FILLET WELD



(c) POSITION OF TEST PLATES FOR VERTICAL FILLET WELD

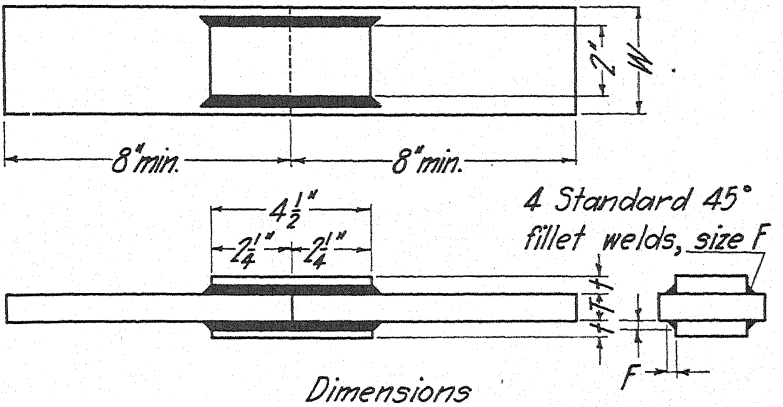


(d) POSITION OF TEST PLATES FOR OVERHEAD FILLET WELD



(e)

Fig. 2—Positions of Test Plates for Fillet Welds



Dimensions

Size of weld F, in.	1/8	1/4	3/8	1/2
Thickness t, in., min.	3/8	1/2	3/4	1
Thickness T, in.	3/8	3/4	1	1 1/4
Width W, in.	3	3	3	3 1/2

Fig. 3—Longitudinal Fillet-Weld Shearing Specimen After Welding

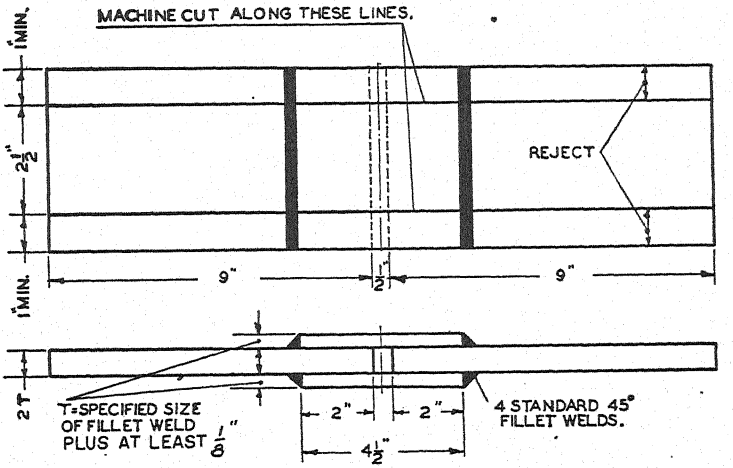


Fig. 4—Transverse Fillet-Weld Shearing Specimen

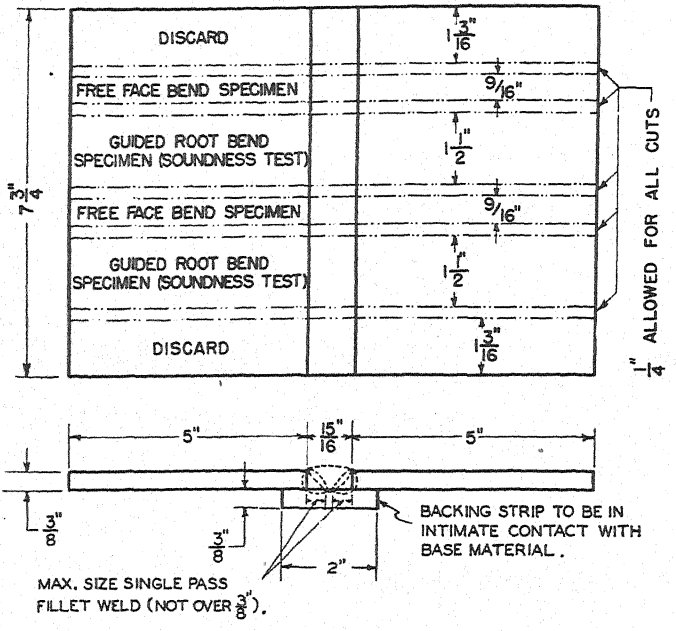


Fig. 5—Test Weld for Free-Bend and Soundness Tests

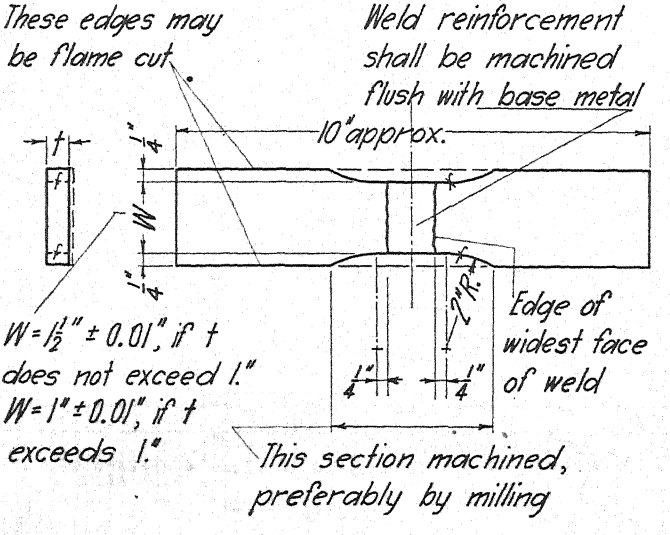
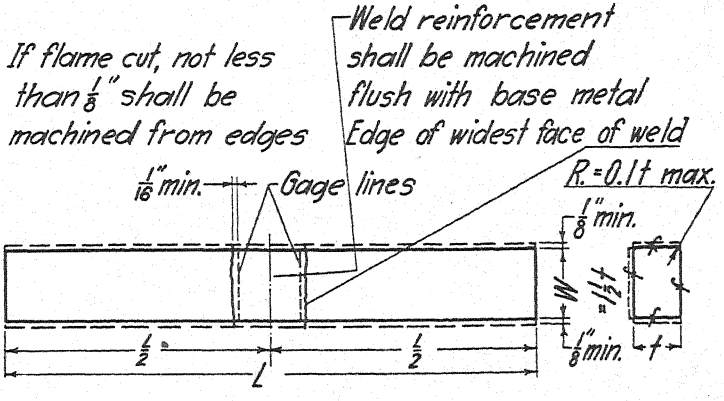


Fig. 6—Reduced-Section Tension Specimen (Plate)

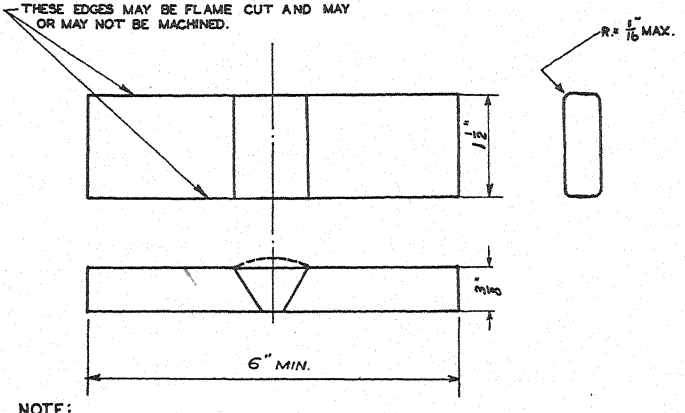


Dimensions

t, in.	3/8	3/4	1	1 1/4	1 1/2	2	2 1/2
W, in.	9/16	1 1/8	1 1/2	1 7/8	2 1/4	3	3 3/4
L min, in.	8	11	12	13 1/2	15	18	21
B* min, in.	1 1/4	2	2	2	2	2	3

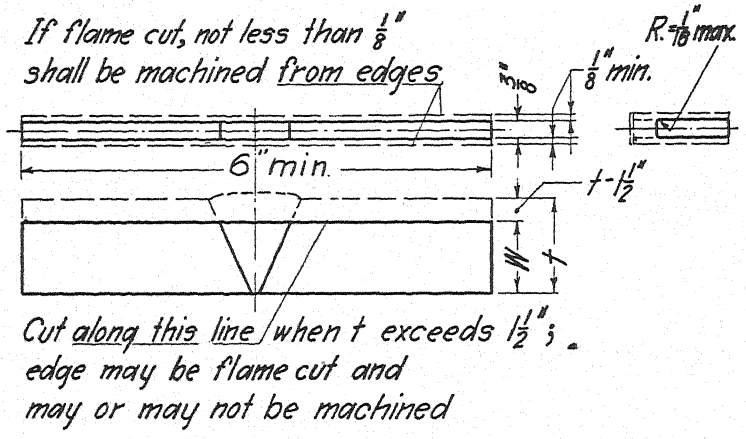
*SEE FIG. 18.
NOTE 1: THE LENGTH L IS SUGGESTIVE ONLY, NOT MANDATORY.
NOTE 2: IF DESIRED, THE EDGES OF THE SPECIMEN MAY BE PREPARED BY MACHINE FLAME CUTTING, FOLLOWED BY ROUNDING OF THE CORNERS WITH A FILE, THOUGH THIS MAY BE A MORE SEVERE TEST.

Fig. 7—Free-Bend Specimen (Plate)



NOTE:
WELD REINFORCEMENT AND BACKING STRIP, IF ANY, SHALL BE REMOVED FLUSH WITH THE SURFACE OF THE SPECIMEN. IF A RECESSED STRIP IS USED THIS SURFACE OF THE SPECIMEN MAY BE MACHINED TO A DEPTH NOT EXCEEDING THE DEPTH OF THE RECESS TO REMOVE THE STRIP, EXCEPT THAT IN SUCH CASES THE THICKNESS OF THE FINISHED SPECIMEN SHALL BE THAT SPECIFIED ABOVE.

Fig. 8—Face- and Root-Bend Specimens (Plate)



t, in.	W, in.
3/4" to 1 1/2"	t
> 1 1/2"	1 1/2"

Fig. 9—Side-Bend Specimen

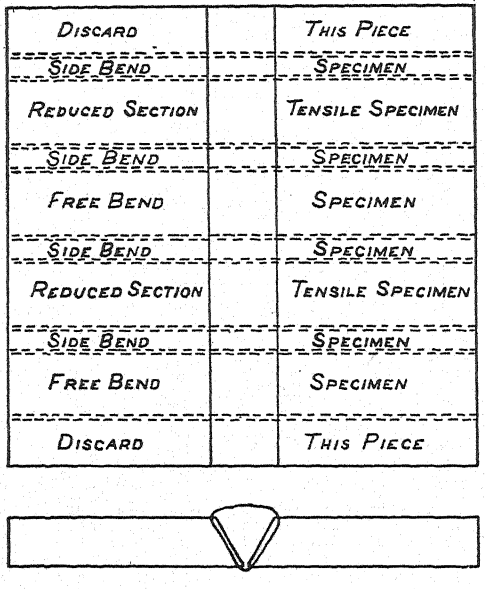


Fig. 10—Order of Removal of Test Specimens from Welded Test Plate (for Plate Over 3/4 In. Thick)

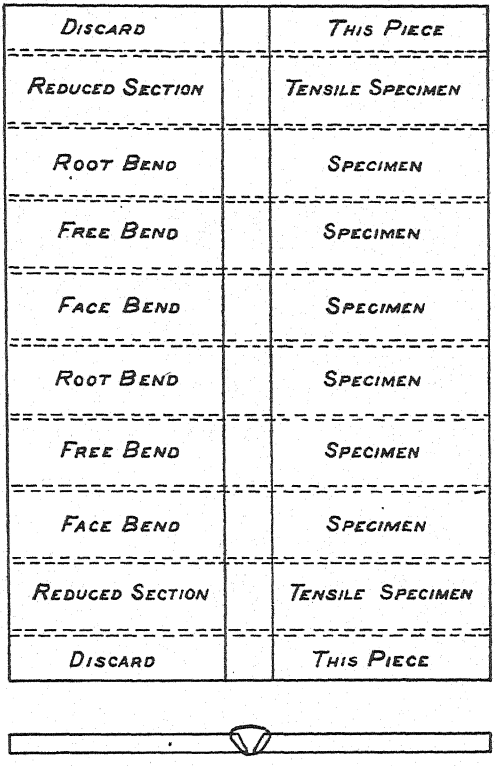


Fig. 11—Order of Removal of Test Specimens from Welded Test Plate (for Plate 3/8 In. Thick)

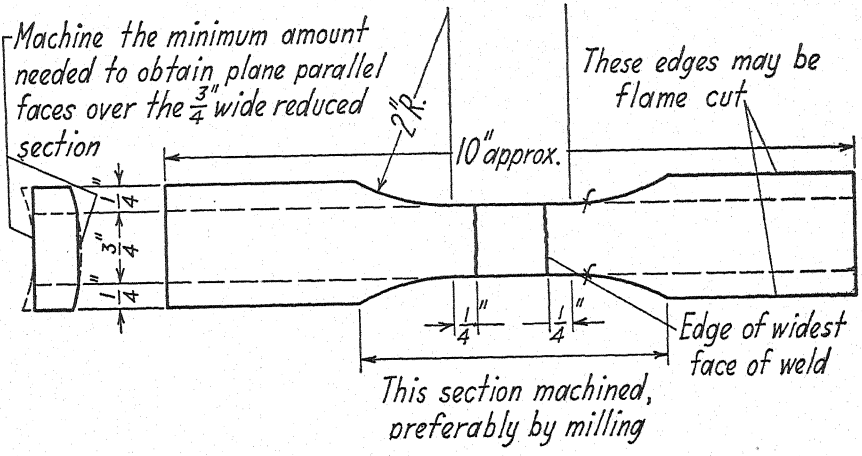


Fig. 12—Reduced Section Tension Specimen (Pipe)

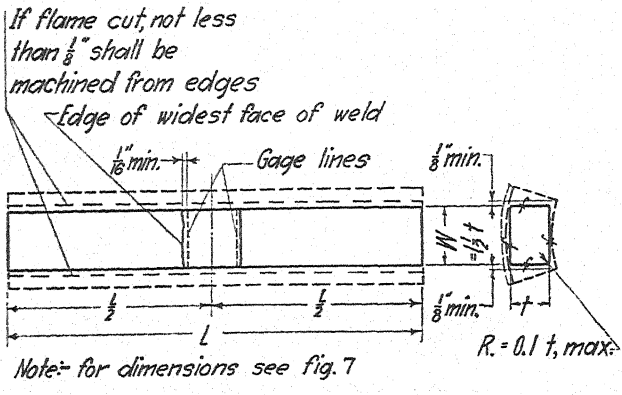
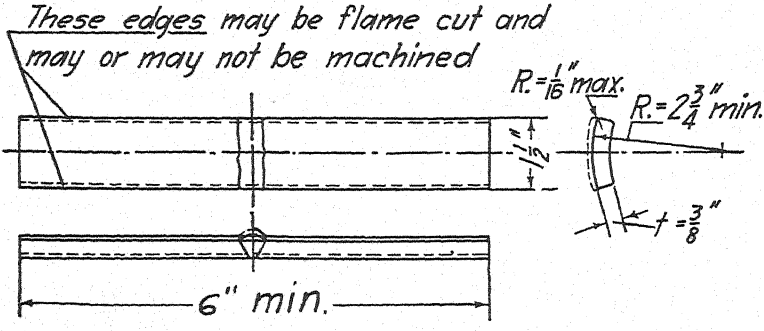


Fig. 13—Free-Bend Specimen (Pipe)



NOTE: Weld reinforcement and backing ring, if any, shall be removed flush with the surface of the specimen If a recessed ring is used, this surface of the specimen may be machined to a depth not exceeding the depth of the recess to remove the ring, except that in such cases the thickness of the finished specimen shall be that specified above

Fig. 14—Face- and Root-Bend Specimens (Pipe)

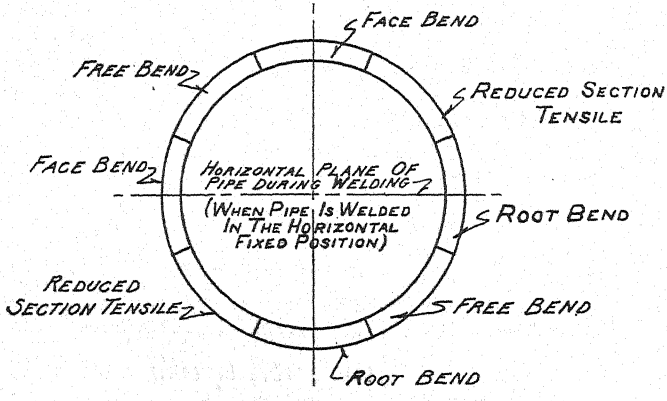


Fig. 15—Order of Removal of Test Specimens from Welded Pipe (for Pipe 3/8 In. Thick

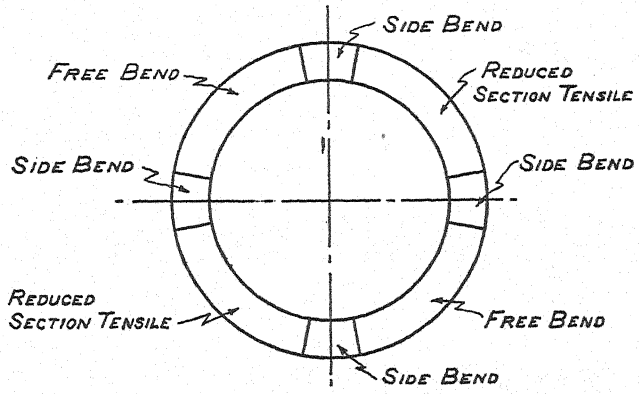
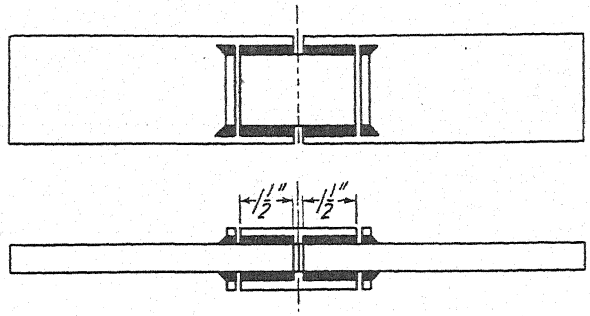
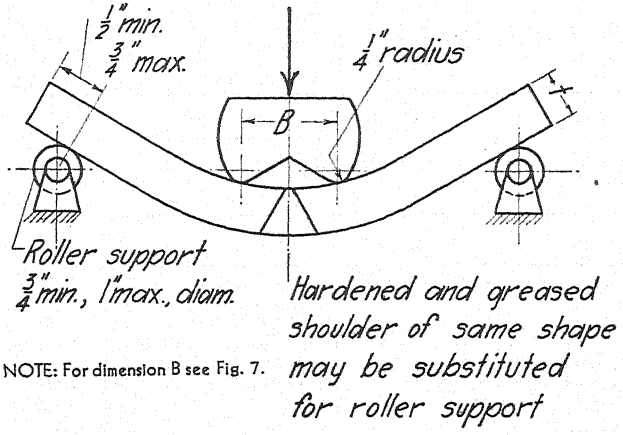


Fig. 16—Order of Removal of Test Specimens from Welded Pipe (for Pipe Over 3/4 In. Thick)



Note—for other dimensions see Fig. 3

Fig. 17—Longitudinal Fillet-Weld Shearing Specimen After Machining



NOTE: For dimension B see Fig. 7.

Fig. 18—Initial Bend for Free-Bend Specimens

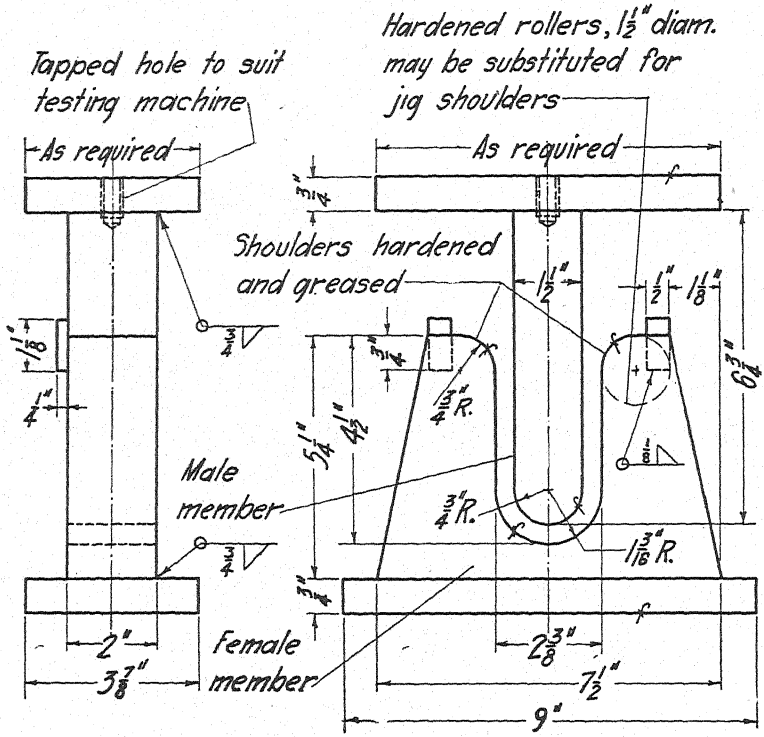


Fig. 19—Guided-Bend Test Jig

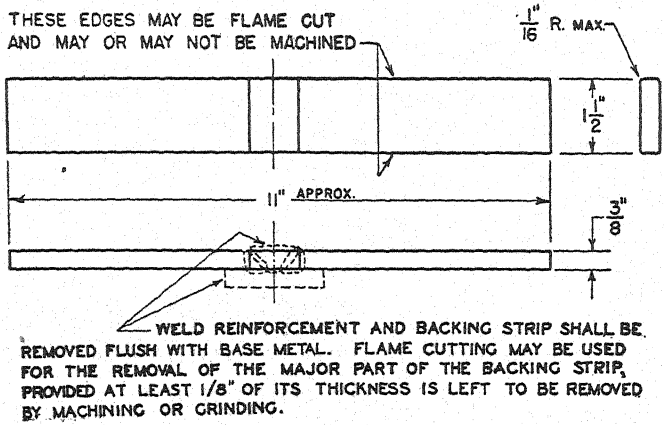
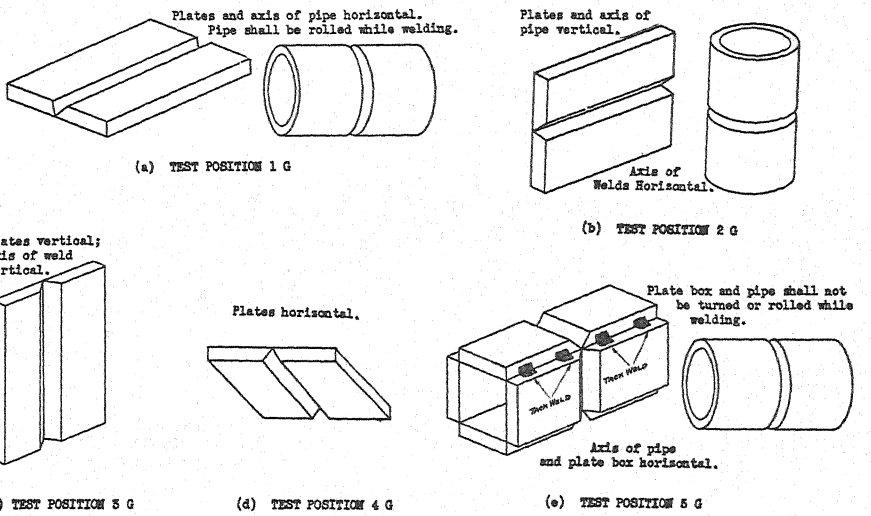


Fig. 20—Fillet-Weld-Soundness Test Specimen



NOTE: For procedure qualification the type of groove shall comply with the Procedure Specification; for operator qualification the shape of the groove and backing strip shall be as shown in Figs. 22, 23, 24 and 25.

Fig. 21—Positions of Test Plates or Pipe for Groove Welds

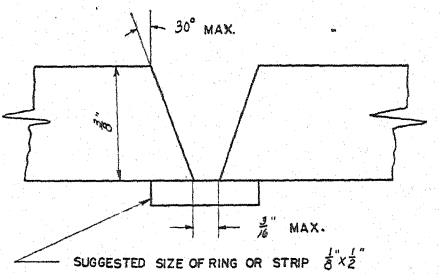


Fig. 22—Butt Joint for Operator Qualification, for Plate or Pipe 3/8 In. Thick

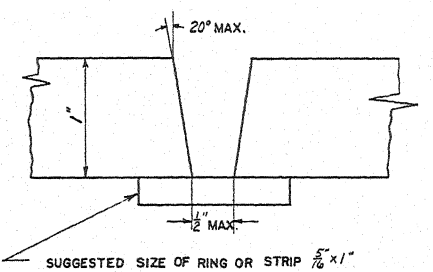


Fig. 23—Butt Joint for Operator Qualification, for Plate or Pipe 1 In. Thick

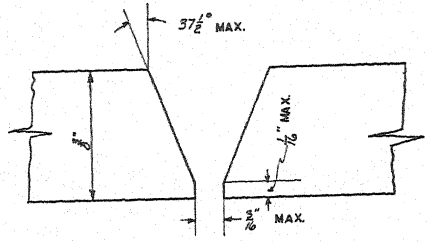


Fig. 24—Alternate Butt Joint for Operator Qualification, for Plate or Pipe 3/8 In Thick (May Be Used for the Oxyacetylene Process Only)

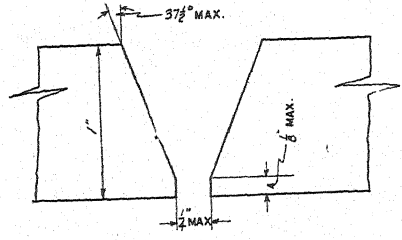


Fig. 25—Alternate Butt Joint for Operator Qualification, for Plate or Pipe 1 In. Thick (May Be Used for the Oxyactylene Process Only)

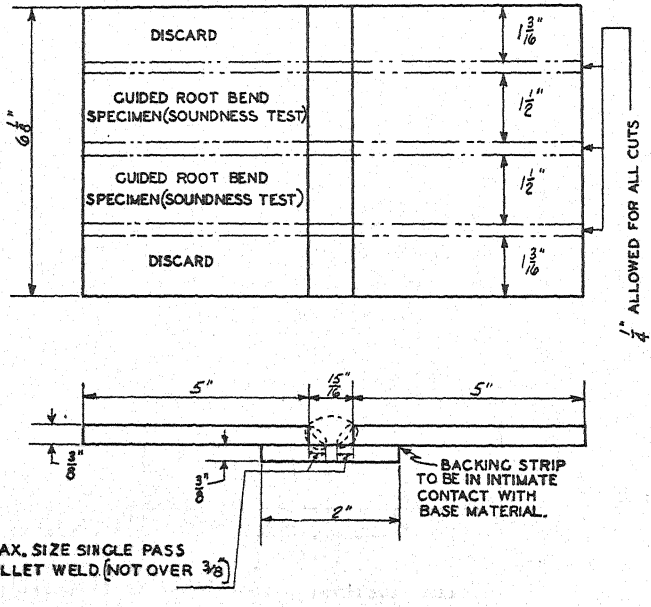


Fig. 26—Test Weld for Soundness Tests (for Operator Qualification Only)

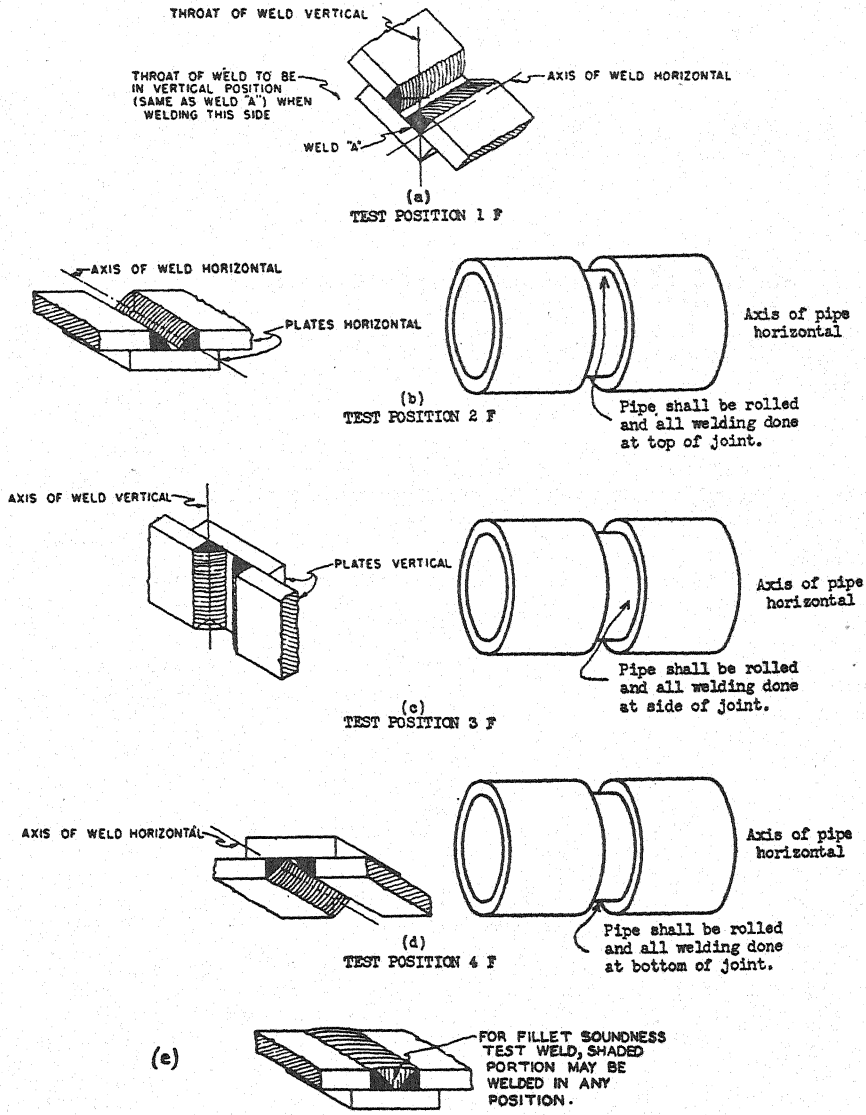


Fig. 27—Positions of Test Plates or Pipe for Fillet Welds (for Operator Qualification Only)

APPENDIX

RECOMMENDED FORMS OF PROCEDURE SPECIFICATIONS

I. Carbon Arc Welding Process:

PROCEDURE SPECIFICATION FOR CARBON ARC WELDING OF

(State Class of Object to be Welded)

Specification No.....

Date.....

Process: The welding shall be done by the Carbon Arc Process.

Base Metal: The base material shall conform to the Specifications for (insert here references to standard A. S. T. M. or other Code designations, or give the chemical analysis and physical properties).

Filler Metal: The filler metal shall conform to Classification Number —— of the American Welding Society's Specification for (insert here the title of the desired specification).

Position: The welding shall be done in the (give the position or positions in which the welding will be done. See Article 104.)

Preparation of Base Material: The edges or surfaces of the parts to be joined by welding shall be prepared by (state whether sheared, machined, ground, gas cut, etc.), as shown on the attached sketches and shall be cleaned of all oil or grease and excessive amounts of scale or rust, except that a thin coat of linseed oil, if present, need not be removed. (The sketches referred to should show the arrangement of parts to be welded with the spacing and details of the welding groove, if used. Such sketches should be comprehensive and cover the full range of material or base metal thicknesses to be welded.)

Size of Carbon or Graphite Electrodes: The range in size of carbon or graphite electrodes shall be as shown on the attached sketch. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set. They should show the range of electrode sizes for each thickness of material.)

Nature of Electric Current: The current used shall be (state whether direct or alternating and if alternating give the frequency). The base material shall be on the (state whether negative or positive) side of the line.

Method of Welding: The method of welding used shall be that known as (describe whether "backhand" or "forehand").

Current Characteristics: The approximate voltage and amperage during welding shall be as shown on the attached sketches. (The sketches referred to may be the same as those under "Preparation of Base Material" or under "Number of Layers and Passes of Welding.")

Size of Welding Rod: The size of rod used for the various base material thicknesses shall be as shown on the attached sketches. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set.)

Number of Layers and Passes of Welding: The number of layers and passes of welding used shall be as shown on the attached sketches. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set. They should show the range of thicknesses for which one, two or more layers are used.)

Cleaning: All slag or flux remaining on any bead of welding shall be removed before laying down the next successive bead.

Defects: Any cracks or blow-holes that appear on the surface of any bead of welding shall be removed by chipping, grinding or gas gouging before depositing the next successive bead of welding.

Peening: (If peening is to be used, it shall be incorporated as part of the Specifications, a description being given of the degree of peening to be done.)

Treatment of Under Side of Welding Groove: (The method of preparing the under or second side of a groove for welding on that side should be stated in this paragraph.)

Preheating: (This paragraph should describe any preheating that will be done.)

Heat Treatment: (This paragraph should describe any heat treatment or stress relieving that is given the welded parts before or after welding.)

Name of Manufacturer

II. Metal Arc Welding Process:

PROCEDURE SPECIFICATION FOR METAL ARC WELDING OF

(State Class of Object to be Welded)

Specification No.....

Date.....

Process: The welding shall be done by the Metal Arc Process.

Base Metal: The base material shall conform to the Specifications for (insert here references to standard A. S. T. M. or other Code designations, or give the chemical analysis and physical properties).

Filler Metal: The filler metal shall conform to Classification Number —— of the American Welding Society's Specification for (insert here the title of the desired specification).

Position: The welding shall be done in the (give the position or positions in which the welding will be done. See Article 104.)

Preparation of Base Material: The edges or surfaces of the parts to be joined by welding shall be prepared by (state whether sheared, machined, ground, gas cut, etc.), as shown on the attached sketches and shall be cleaned of all oil or grease and excessive amounts of scale or rust, except that a thin coat of linseed oil, if present, need not be removed. (The sketches referred to should show the arrangement of parts to be welded with the spacing and details of the welding groove, if used. Such sketches should be comprehensive and cover the full range of material or base metal thicknesses to be welded.)

Nature of Electric Current: The current used shall be (state whether direct or alternating and if alternating give the frequency). The base material shall be on the (state whether negative or positive) side of the line.

Welding Technique: The welding technique, electrode sizes, and mean voltages and currents for each electrode shall be substantially as shown on the attached sketches. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be separate sketches. They should show for the minimum thickness and for several intermediate thicknesses of base material, the welding technique to be used, whether weaving or beading, the number of layers or passes and diameter of electrode with the mean voltage and current for each layer or pass, and in the case of vertical welds, the progression of each pass, whether upward or downward.)

NOTE: Since, in the welding of many materials in the flat position and particularly for the ordinary mild steels, the proper welding "heat" can be readily determined by the appearance of the individual beads of welding, the use of a "Standard Appearance Weld" may be desirable for the flat position. Such a weld should be made in the maximum thickness that will be used in construction, except that the maximum thickness of the Standard Appearance Weld need not exceed $^3/_4$ in., and should show approximately 2 in. of the surface of each layer and a cross section through the weld at each layer, where such cross section is found necessary to produce a clearly understandable photograph. When a Standard Appearance Weld is used the following paragraph should be used in lieu of specifying current and voltage values.

Appearance of Welding Layers: The welding current and manner of depositing the weld metal shall be such that the layers of welding as deposited shall have the appearance shown on the photographs attached hereto. There shall be practically no undercutting on the side walls of the welding groove or the adjoining base material.

Cleaning: All slag or flux remaining on any bead of welding shall be removed before laying down the next successive bead.

Defects: Any cracks or blow-holes that appear on the surface of any bead of welding shall be removed by chipping, grinding or gas gouging before depositing the next successive bead of welding.

Peening: (If peening is to be used, it shall be incorporated as part of the Specifications, a description being given of the degree of peening to be done.)

Treatment of Under Side of Welding Groove: (The method of preparing the under or second side of a groove for welding on that side should be stated in this paragraph.)

Preheating: (This paragraph should describe any preheating that will be done.)

Heat Treatment: (This paragraph should describe any heat treatment or stress relieving that is given the welded parts before or after welding.)

Name of Manufacturer

III. Oxyacetylene Welding Process:

PROCEDURE SPECIFICATION FOR OXYACETYLENE WELDING OF

(State Class of Objects to be Welded)

Specification No.....

Date.....

Process: The welding shall be done by the Oxyacetylene Process.

Base Metal: The base material shall conform to the Specifications for (insert here references to standard A. S. T. M. or other Code designations, or give the chemical analysis and physical properties).

Filler Metal: The filler metal shall conform to Classification Number —— of the American Welding Society's Specification for (insert here the title of the desired specification).

Position: The welding shall be done in the (give the position or positions in which the welding will be done. See Article 104.)

Preparation of Base Material: The edges or surfaces of the parts to be joined by welding shall be prepared by (state whether sheared, machined, ground, gas cut, etc.), as shown on the attached sketches and shall be cleaned of all oil or grease and excessive amounts of scale or rust, except that a thin coat of linseed oil, if present, need not be removed. (The sketches referred to should show the arrangement of parts to be welded with the spacing and details of the welding groove, if used. Such sketches should be comprehensive and cover the full range of material or base metal thicknesses to be welded.)

Size of Welding Tip: The range in size of welding tips used shall be as shown on the attached sketch. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set. They should show the range of tip sizes for each thickness of material.)

Nature of Flame: The flame used for welding shall be (state whether a neutral flame or one with slight excess of acetylene is to be used).

Method of Welding: The method of welding used shall be that known as (describe whether "backhand" or "forehand").

Size of Welding Rod: The size of rod used for the various base material thicknesses shall be as shown on the attached sketch. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set.)

Number of Layers of Welding: The number of layers of welding used shall be as shown on the attached sketches.(The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set. They should show the range of thicknesses for which one, two or more layers are used.)

Cleaning: All slag or flux remaining on any layer of welding shall be removed before laying down the next successive layer.

Defects: Any cracks or blow-holes that appear on the surface of any layer of welding shall be removed by chipping, grinding, or gas gouging before depositing the next successive bead of welding

Peening: (If peening is to be used, it shall be incorporated as part of the Specifications, a description being given of the degree of peening to be done.)

Treatment of Under Side of Welding Groove: (The method of preparing the under or second side of a groove for welding on that side should be stated in this paragraph.)

Preheating: (This paragraph should describe any preheating that will be done.)

Heat Treatment: (This paragraph should describe any heat treatment or stress relieving that is given the welded parts before or after welding.)

Name of Manufacturer

CHAPTER 30

RECOMMENDED PRACTICES FOR INSPECTION OF FUSION WELDING*

AS IN the case of much fabricated work, that which is done by a welding process is often required to be inspected during the course of construction, either by the purchaser, by the manufacturer or by reason of some legal code requirements. Whatever the reason, inspectors must be employed by either the fabricator, the purchaser or some agency engaged in furnishing inspection services.

In any event an inspector acts in a judicial capacity as the responsible representative of an organization. He must be governed by some form of written requirements for which he is not likely to have been responsible. If he acts for a purchaser, these may be purchase specifications or some construction code. If he acts for a state, municipal or federal agency they may be definite codes which are civil law or departmental rules. An inspector is guided by the prescribed requirements in either accepting or rejecting the work.

It is not possible to specifically cover all methods of welding or all kinds of material. However, the principles set forth herein are quite generally applicable.

While there are certain characteristics desirable in an inspector it is unwise to attempt to lay down any mandatory requirements, hence the section on qualifications of inspectors is intended only to indicate in general terms the desirable aptitudes.

The structures on which inspection is required will vary widely in design and type of welding application so that no one class of inspectors can be expected to be proficient in all of them.

A shop inspector employed by the manufacturer makes certain routine checks of materials, dimensions, workmanship, finish and other details in a manner that will insure that the product meets design requirements. Such inspection is as much a part of production as the necessary machine operations.

Independent inspections must be on a basis different from that of routine shop inspection. It is generally physically impossible for an inspector to check all details of each part of the product. Any such checks must

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either be limited to spot checks or random samples, or else made only when the inspector has reason to believe that code or specification requirements are not being met.

It is always advantageous for an inspector to have had practical experience in producing the product he inspects. Theoretical or reading knowledge of the work does not inspire the confidence of the manufacturer's personnel that actual working experience does. On the other hand, practical experience alone, without the other necessary qualities, is not sufficient equipment for a capable inspector.

The several sections of this report are so segregated as to make the recommended practices readily available to those interested and are in as much detail as is possible without becoming too elaborate.

The practices among different fabricating shops vary due to location, equipment and various ideas which have been gained through experience, although the final result should be the same. Inspectors who have had experience only in one or two shops should not attempt to convert other fabricators to the practices with which the inspectors are familiar. Should this be attempted, the result is likely to be increased cost of fabrication, confusion due to unfamiliar methods and a general animosity toward the inspector covering the work. The inspector should enter a shop with two main thoughts in mind, namely, to obtain a good job properly fabricated to the applying code or other specification and to expedite the completion and delivery as much as possible. A capable inspector has the advantage of knowing what should be furnished and just what his employer wants, whereas the fabricator, in many cases, is handicapped, particularly in the shop, in not being fully informed and familiar with the product.

Believing that it will be helpful to inspectors, a discussion of the problems encountered in the welding of ferrous and non-ferrous metals has been included.

SECTION I—QUALIFICATIONS OF WELDING INSPECTORS

An inspector should have excellent eyesight, and his physical strength and agility should be sufficient to permit efficient work. He should be familiar with the code which governs the work he is inspecting. The codes most commonly used and generally recognized are those of the Boiler Code Committee of the American Society of Mechanical Engineers, the A.P.I.-A.S.M.E. Unfired Pressure Vessel Code, the A.W.S. Code for Arc and Gas Welding in Building Construction, the A.W.S. Rules for Field Welding of Steel Storage Tanks, the A.W.S. Specifications for Welded Highway and Railway Bridges, the A.W.S. Standard Qualification Procedure and the welding specifications of the bureaus of the Navy Department and War Department. He must, of course, also be familiar with any other specifications under which the work he is to inspect is to be done.

The inspector should have had actual experience in the inspection of welding. It is usually an advantage for him to have had personal experience in welding by either or both the electric arc and oxyacetylene processes. While it is not essential, technical education is very desirable. He should be competent to determine, by observing the actual welding operation, whether an operator is securing proper fusion and penetration.

He should be conversant with filler metal specifications covering electrodes and welding rods and know the limitations of the several grades.

He should be familiar with the various non-destructive tests for welding and be able to interpret and evaluate accurately the results of such tests.

The inspector's temperament should be such that he is able to cooperate fully with the manufacturer, to the end that the required results are obtained and amicable relations are preserved between the purchaser and the fabricator.

He should have unfailing integrity in the prosecution of the work and honesty in his dealings with the manufacturer.

He should have good judgment in the interpretation and application of code or specification requirements since even the most carefully prepared rules are not always clear or complete.

He should be familiar with the reading of drawings, particularly with respect to understanding of the symbols for welding.

He should have sufficient technical training or experience to realize the possible effect of heat during welding on the strength of the structure and its relation to cracking and other defects. He should know what constitutes a good weld and how to detect any defects that might occur.

He should have ability to prepare complete, concise and readily understandable reports.

SECTION II—DUTIES OF INSPECTORS

In outlining the duties of inspectors on welded fabrication work it will be assumed that they are competent to make the kind of inspections needed for the type of structure to be inspected.

If it is so stipulated in the instructions under which the inspector is working, one of his functions may be to act as intermediary between the customer and the fabricator from the time the plates and other material are ordered until the vessel or other structure is finally completed. Sometimes it may be expedient, although it is rarely a part of his duties, for the inspector to be of service by acting as expeditor of materials from various mills since his familiarity with the job and foresight can thus avoid delays in delivery.

An inspector should be alert at all times, not because the fabricator may intentionally disregard certain requirements but because of errors that may occur through carelessness or lack of familiarity on the part of the fabricator with the customer's specifications or the code to which the vessel is being built.

The duties of the inspector on welded construction will, for most structures, follow the order of fabrication procedure, which generally starts with (*a*) the design and materials to be used, and continues with (*b*) methods of assembly and fitting up, (*c*) checking of the procedure and qualification of operators, (*d*) inspection during construction, (*e*) proof or acceptance tests and (*f*) records. These items are elaborated upon below.

Design and Materials

The inspector should study the design in advance, particularly with respect to the loads to be carried by the several parts and the construction details of the work with special reference to the provisions made for welded fabrication.

It is also important to consider the material used in the structure as some

materials, such as alloy steels or the non-ferrous metals, may require special treatment to obtain satisfactory welding. The welding details and materials should be checked by the inspector before fabrication begins, for compliance with the applicable code or specification.

Assembly and Fitting Up

In those cases where it is required the inspector must have opportunity to check the fitting and alignment of parts to make sure that the welds can be applied to meet the requirements of the design and that the stresses will be distributed as intended. He should also carefully follow the welding operations to make sure that warpage and misalignment will be avoided to the greatest possible extent and thus avoid possible rejection.

Procedure and Operator Qualification

It is a fundamental principle that the manufacturer must adopt a definite procedure by which the welding in the shop or field is to be done. This procedure should be such as to deposit weld metal and produce welded joints with acceptable characteristics as called for by the guiding specification or code. It is part of the inspector's duty to witness the demonstration test to prove the sufficiency of the procedure, or to see authentic documentary evidence to that effect. This procedure should be written out, giving in detail all pertinent data such as the type of electrode or rod to be used, the shape of the welding groove, the number and sequence of the several beads, cleaning of slag, peening and the current characteristics for electric welding or the size of tip and nature of flame, forehand or backhand technique, etc., for gas welding.

If the work is to be done under the terms of an established code, the qualification test to demonstrate that the welding procedure to be used is suitable for the purpose will probably have been provided for. It will be required also that the welding operators be checked by suitable tests to determine their ability to apply the procedure selected and obtain sound welds. If, however, the work is not subject to any particular code rules, specifications or contractual requirements may impose some qualification procedures which the inspector should see are properly followed.

Inspection During Construction

Inspections on which acceptance of the welded structure will be based are usually made in the manufacturer's or contractor's shop when the work is of such dimensions that when completed it can be shipped or transported to the installation site. If the work exceeds the limiting dimensions of shipping facilities it must be fabricated at the place of erection, either in whole or by erecting parts and sections that were prefabricated in the shop. In the former case the inspection is all carried on in the field while in the latter the inspection is divided between the fabricating shop and the field erection site.

Inspection of new work in the shop or in the field can be properly made only when there are code requirements or specifications for the guidance of the inspector, together with detailed drawings showing just how the various parts are prepared, shaped and joined together.

It is the welding operator's duty to be guided by the specified procedure when making welds, but prior to doing any work on a welded structure, he

must have demonstrated his ability to make sound welds when following the prescribed procedure. It is the inspector's duty to assure himself that each welding operator has made a satisfactory qualification test, either by seeing the test made or by checking the results of tests previously made and which should be part of the shop record. Only such operators should be permitted to work on welded structures coming under the inspector's jurisdiction.

Testing

After fabrication is completed it is an important duty of the inspector to check the structure to make sure that all code or specification requirements have been met. This may, in many classes of work, involve some tests or other special treatments. In pressure vessel construction, stress relieving, radiographing, trepanning or hydrostatic testing may be required. For other weldments, one or more of these requirements may be applicable. Pressure vessels and parts are required to be subjected to hydrostatic tests to determine their tightness as well as also to obtain some indication of the strength of the welds.

Records

Work that requires inspection will also require adequate records but whether required or not the inspector should keep full notes of his inspection work.

It is his duty to check the required records to make certain that they are complete, in accordance with the rules, accurate and available when and as required. Records that require the manufacturer's signature should be prepared by the manufacturer.

Records should be in as much detail as the conditions necessitate. It is well to comment on the general character of the work, such as the observance of prescribed tolerances, any difficulties under which the whole or any part of the work may have been performed and any defects that there may have been, whether corrected or not.

The inspectors should see that copies of the records go to the manufacturer, contractor or any others entitled to them, retaining a copy in his own file for future reference.

SECTION III—INSPECTION AND TESTING OF WELDED STRUCTURES

General

The increased use of welding in the fabrication of pressure vessels and other structures has made it necessary for inspectors covering this class of work to familiarize themselves with the many phases of welding in connection with such fabrication.

The inspectors must not only be familiar with the actual welding but should have a knowledge of the material being used, physical testing, shop practices, stress relieving, radiographic examination as well as many other points.

The inspection of welding operations properly falls under two headings: (1) the examination of welding techniques and (2) the evaluation of weld

quality through the application of standard tests. The former requires an intimate practical knowledge of welding operations while the latter calls for complete familiarity with the standard American Welding Society tests. which are written in terms of results, independent of the process used. From this it may be seen that the only difference in inspecting arc and oxyacetylene welding operations lies in the inherent differences between the two processes.

The testing of welds is the same for both arc and gas welding. It should be remembered that in all weld testing there are relatively few non-destructive tests. All of the tests employed in qualifying procedures and operators (see A.W.S. Standard Qualification Procedure) are definitely destructive tests and consequently are not practicable for finished structures.

There are several non-destructive tests available—X-ray, gamma ray, trepanning, magnetic powder testing—but unfortunately none of them may be considered universally applicable. These tests are principally qualitative in results, although a measure of quantitative evaluation is possible in the case of X-ray and gamma ray examination.

The X-ray and gamma ray methods of testing, while differing in application and technique of execution, are sufficiently alike in results to permit considering them together.

The pressure test (hydrostatic or air) is suited only to closed containers, such as pressure vessels, tanks, pipes, etc.

The following comments apply principally to welded pressure vessels but the general principles are applicable to any forms of welded structures.

Shop Inspections

1. Materials

The materials used in the fabrication of welded structures must be of a weldable quality and should meet the requirements of the specifications for such materials. These factors should have been thoroughly considered at the time the structure was designed and during the inspection of the raw materials at the mills. If such inspection is provided, it should be seen that the specified requirements are complied with. Lacking inspection at the mill, the mill test reports should be carefully checked. If these precautions are not taken, difficulties which can be attributed to improper materials may be later encountered during the welding.

The plates, shapes, heads, forgings, etc., should preferably be inspected at the various sources of supply, but, wherever inspected, any materials which show injurious defects should be rejected.

The materials should have been tested as to physical properties and these, together with the chemical analyses, should meet the specified requirements. If the finished structure is to be stress relieved or given any special heat treatment, it should be determined that the acceptance tests are made on specimens receiving the same treatment. A record of all test results and analyses should be kept for reference during fabrication and after the structure has gone into service.

If the specifications require the material to be stamped, the inspector should see that the proper markings are applied with steel stamps as these may be required in the course of fabrication or later for identification in the field after the equipment has been placed in service.

The inspection of plate edges by etching or testing, by the gas torch or otherwise, will disclose any discontinuities or laminations which, if present to a marked degree, become a factor contributing to weld defects, particularly with the submerged melt process of welding. Laminations may, in some cases, be chipped out and the groove filled by manual welding before welding the joints.

2. Fabrication

The edges of the plates, shapes, heads or other surfaces where welding is involved should be properly prepared for welding. The most common joints in welding are the butt type, using a V, U or modified U groove, and the fillet type. The root face should be of uniform thickness in order to avoid difficulties during the deposition of the first few beads of weld metal at the bottom of the groove. The uniformity with which this is held lessens the possibility of not removing sufficient metal when chipping for back welding, since the chipper will have a uniform amount of metal to remove.

The edges of rolled plates should have the proper curvature in order to avoid a flat zone along the seam.

After the plates or shapes have been formed to the proper diameter or shape, the fit-up prior to welding should be checked to see that the edges are properly butted or fitted and held in place by tack welds or other means.

In fitting up shell sections and/or heads or other parts for welding of the circumferential and other joints, the alignment should be carefully checked to avoid any improper practices which would necessitate lengthy and costly repairs later, with resulting delays in completion.

3. Welding

All welding operators to be employed on the job should be qualified in accordance with the particular specification or code to which the structure is being fabricated. The fabricator's records of operators' qualification tests should be checked to see whether all operators have satisfactorily passed the tests required within the prescribed time limit. A point to be checked in this respect is to see whether each operator has been qualified individually on plates of the thickness being welded and not on a plate made by several operators. It should also be ascertained that welding operators who are to be employed on work not in a flat position or on assemblies such as piping, are qualified for welding in the position in which the work must be performed. This should be gone into thoroughly and each operator employed on the work qualified before welding operations are started.

The type of electrode or rod to be used should be checked. Although there are a number of satisfactory coated electrodes, it is usually advantageous to use the same one throughout the job. The storage room for electrodes should be checked since damp or humid atmospheres can have a detrimental effect on the coating and an unsatisfactory weld result. The welding characteristics of the machines should also be investigated to determine that uniform welds of high quality can be obtained.

The practice in most cases is to weld the seams in pressure vessels on the outside, then back chip and complete the weld on the inside. Care should be taken to see that all unfused metal, cracks, etc., are removed at the bot-

tom of the weld before backwelding, and that the chipped groove is smooth and of the proper contour to permit backwelding without the entrapment of slag, since this is one of the vital points in obtaining a sound and homogeneous weld. In the case of ferrous materials, magnetic powder inspection of the root-chipped groove may be performed in case there is doubt concerning the complete removal of defects in the bottom of the groove. The welding technique for identical jobs will vary in different shops but equally satisfactory results can be obtained. The customer is primarily interested in obtaining a sound weld and a satisfactory product, and it is not a function of the inspector to dictate the technique to be used.

Particularly for heavy plates, high tensile steels or alloy steels, the procedure will probably call for preheating. There are no hard and fast rules for preheating temperatures but in any case the inspector should guard against permitting the metal in the vicinity of the weld to drop to a temperature below that specified in the approved procedure.

Each bead of welding should be thoroughly cleaned of all slag before applying each successive bead. The cleaning operation is essential as many defects in welds can be attributed to improper cleaning. In finishing a weld the last bead should be made so that a uniform, neat looking weld will result. Undercutting should be guarded against and any undercut areas should be repaired by applying a stringer bead over the undercutting, which later should be chipped and ground flush with the plate. The fillet welds of all connections, such as manways, nozzles, attachments, etc., should be at the correct angle and of the proper depth. There is a tendency to apply most of the weld metal of a fillet weld on one leg and have insufficient depth through the throat.

The first layer of fillet welds should be made with an electrode small enough to assure penetration into the root of the joint.

4. Examination of Welds

Many specifications and codes provide for some sort of non-destructive examination of welds, such as X-ray, gamma ray, magnetic powder testing or a sectioning method, as described below.

Radiography, particularly with X-rays, is a common nondestructive method of examining welds. If the equipment is of sufficient capacity for the thickness of plate involved, this examination should reveal any defects or inclusions that are 2% of the plate thickness or greater. As a means of determining this, suitable penetrameters are provided for in the codes. The penetrameters should be properly attached and identified with numbers as to their location. If any film does not show the proper identification numbers or if the required penetrameter indication is not picked up, the radiograph should be retaken.

The technique used in taking X-rays depends largely on the equipment which the fabricator has and what his experience has shown will produce the best results. It is not the function of the inspector to dictate the procedure to be followed provided the films resulting from the fabricator's practice are satisfactory. The manufacturers of X-ray equipment set up certain procedures applicable to their machines. However, in most instances it has been found necessary to vary from these set rules in order to obtain the best results. (See Chapter 33B.)

The interpretation of radiographic films requires not only a knowledge

of welding and welding defects but also the exercise of good judgment as to whether the questionable area is actually a defect. Where a difference of opinion exists, rather than cut out the weld, a retake of the areas in question may prove whether the welding is sound or not. Other areas may be questioned that may be the result of a low spot in the weld, undercutting, an inside seam line or other conditions which are not usually considered to be welding defects. In such cases the film should be placed on the weld and the areas in question located on the surface and the necessary corrections made. The removal of slag, cracks, lack of fusion and other obvious defects is seldom questionable and the defective areas must be chipped out, rewelded and re-X-rayed. However, the interpretation of porosity resulting from gas inclusions and the extent to which such porosity can be accepted have constituted a source of some disagreement in the past. This has been largely eliminated through the adoption of standard films by the A.P.I.-A.S.M.E. and the A.S.M.E. Codes, showing what is not acceptable. The use of these standard films, together with a knowledge of welding and the application of good judgment, should result in a satisfactory product and keep any discussions between the fabricator and inspector to a minimum.

When complete X-raying is not specified, the welds may be examined by taking spot X-rays at points indicated by the inspector.

In heavy-wall structures or those where X-raying is not practicable, radium is sometimes used in examining the welds. This is called gamma raying and while the technique of taking the pictures is different, the results are quite similar to X-raying. (See Chapter 33B.)

Where radiographic equipment is not available, examination is often made by a sectioning method such as trepanning plugs or otherwise cutting samples from the welds. Trepanning is done by means of a special cylindrical saw operated by motor, which is readily obtainable. Another method is to saw from the welded joint a boat-shaped specimen by means of a special spherical saw. The plugs should be taken at those points where the welds look questionable. One of the common points where such plugs are taken is at the intersection of circumferential and longitudinal seams. After removal, the plugs should preferably but not necessarily be sectioned so as to get a plane surface, and be etched and examined for objectionable defects, such as cracks, lack of fusion and inclusions. If any are found defective, additional plugs should be taken at intervals on each side of the defective ones. This should be continued until no further defective plugs are found in the particular seam and all welding represented by the defective plugs should be chipped out, rewelded and retested. Where equipment is available, spot X-raying is preferable. (See Section VI for etching reagents and methods.)

The magnetic powder method of testing may also be employed on finished welded products of ferrous material. The metal part is first magnetized, generally by an external coil or solenoid. The magnetized piece is then covered with finely divided iron particles either by sprinkling or by immersing in a bath of light oil in which the particles of iron are kept in suspension by agitation. A crack or defect in the part, either surface or sub-surface, causes a discontinuity in the magnetic flux lines and the iron particles collect at that point, outlining the defect. Again this is a qualitative test and is limited to those assemblies which permit of magnetization.

Considerable experience is required to properly apply and judge the results of this method of testing. (See Chapter 33B.)

5. Stress Relieving

After the welding of all seams and attachments has been completed and all welds repaired, the vessel should be stress relieved if required by the code or purchaser. The stress-relieving furnace should be of a type adaptable to the work involved and designed so that the heat will be applied uniformly and in a manner not injurious to the vessel. In the case of thin shells or shells which may be susceptible to some deformation during the stress-relieving operation, they should be braced on the interior so as to minimize the distortion. The vessel should be blocked in the furnace in such a manner as to prevent sagging or bowing during the stress relieving. The rate of cooling of structures which have a great variation in section should be controlled in order that residual stress will not be set up from excessive temperature differentials in the weldment during the cooling cycle.

The fuel used in the stress-relieving furnace should be checked as certain types of fuels cause heavier scaling or greater oxidization than others. The fuel used in a stress-relieving furnace is not for an inspector to decide but it is well for him to familiarize himself with it, and the conditions that may result from its use, such as excessively heavy scaling. Certain elements in fuels may have a deleterious effect on non-ferrous metals, for example, 0.5% or more of sulphur in a fuel will have an embrittling effect on high-nickel materials and therefore should not be used.

The temperature controls, recording charts, location of thermocouples, etc., should be checked to insure uniformity in the heating of the vessel. The temperature used should conform to the applicable code, and the rate of heating, time held and rate of cooling should agree with the prescribed practice.

6. Hydrostatic Testing of Pressure Vessels

After all other processes or operations required by the specification or code have been performed, the vessel should be hydrostatically tested. The test pressure should be that called for by the code, specification or contract. The vessel should be blocked up for testing in such a manner as to permit examination of all parts during the test period. Sagging due to the water load should be guarded against. When filling the vessel with water, care should be taken to avoid all air pockets. The temperature of the water should be approximately the same as, but not lower than, the atmospheric temperature, otherwise "sweating" will result and a proper examination will be difficult. The telltale holes in the reinforcing pads should not be plugged during the hydrostatic test, and all such pads should be tested prior to the hydrostatic test, this test to consist of applying air pressure on the pad through the $^1/_4$-in. tapped opening and slushing soapy water on the welds, both inside and outside. A gage should be so located as to indicate the air pressure applied to the pad.

The hydrostatic pressure should be applied gradually and the gage checked to see that it is functioning properly. If available, a second gage attached to the vessel at some suitable point is desirable in order to check the pressure readings.

If the code or specification requires a hammer test this should be applied in accordance with the requirements. A small curved steel plate placed over the weld during this test will afford some protection to the shell itself. Hammer testing is a controversial subject and present requirements are likely to be changed. Inspectors should be alert to any new action by code committees.

When the time limit of the test has been reached, a final examination should be made of all seams, telltale holes, etc., and, if the results are satisfactory, the pressure can be released.

The use of air for the testing of pressure vessels is discouraged and should not be employed unless the vessel has first been tested with water to a pressure in excess of the air test pressure. In the case of large gas containers not designed to carry heavy loads, testing by air must be resorted to but should be done only in accordance with a prearranged program.

7. Testing Structures in General

In the case of some welded structures, tests may be applied to determine the integrity of both the structure and the welds used in fabricating or repairing it. In structures formed of welded structural shapes, testing may be applied by loading, lifting or perhaps otherwise overstressing the part to determine whether there is the desired margin or reserve strength available therein. However, the specifications usually provide for any testing desired.

8. Final Inspection and Check of Pressure Vessels

After the hydrostatic test, the vessel should be drained and any silt or scale cleaned out and final inspection of the interior and exterior made, as well as a check of the alignment, circularity and general dimensions. The vessel should be leveled as carefully as possible for this check and the measurements should be accurately taken especially in the case of towers or other vessels which contain tray supports or internals where close tolerances must be held.

During the final inspection any welding which has not been properly cleaned should be ground or chipped to give a satisfactory appearance. Any areas where clips or attachments were welded on for testing or handling should be chipped and ground smooth. The welds should be carefully checked for evidence of cracks which might have developed on test.

If the arrangement for the inspector provides for a more general inspection than merely the welding operations, the over-all dimensions, connections, squareness of flanges, facings, drillings, etc., should be checked to see that they conform to the drawings within the permissible tolerances. Spirit levels and protractors should be used and in checking the elevations of connections and manways, the dimensions should be taken from the base line or working point shown on the drawing. Structures that are to be shipped to other points for machining should be carefully checked for dimensions on all surfaces to be machined to assure that sufficient stock is provided. Insufficient stock can readily be added by welding at the point of fabrication, even though it necessitates re-stress relieving, whereas the machining contractor may have neither welding nor stress-relieving facilities. It is often advantageous to deeply center punch bench marks or base

lines for the convenience of the layout men in the machine shop or in the field. (Center punch marks should not be left on parts which are to resist dynamic loads.)

Upon completion of the tests and inspection, the vessel should be stamped with the design pressure, allowable working pressure, test pressure, code symbol, etc., as required by the applicable code or specification, along with the inspector's identifying marks. The inspector should see that the manufacturer has prepared and signed the proper record forms, and himself sign them if required, retaining one or more copies together with other pertinent data such as the copies of the stress-relieving charts, test charts, weld test results, material data, etc., which should be retained as a permanent record of the vessel.

Field Inspections

1. New Work

Fabricating new work in the field may be considered as only deferred shop operations, to which the same principles apply as for shop work.

2. Existing Structures

The inspection of existing welded structures is not nearly so definite a procedure as that involved in the inspection of new welded construction. The principal purpose of inspection of existing vessels or other structures is to ascertain the physical condition of the object with particular reference to the welded joints and fastenings. It is important to observe whether they have deteriorated either from over-stressing or corrosion and, of course, signs of weakening of the structure should be carefully looked for.

It is obviously impossible to tell by the appearance of the exterior of a welded joint what its interior condition may be but in many instances the condition of welded seams can be quite definitely determined by trepanned plugs as hereinbefore described. In many cases one of the most dangerous effects is corrosion, either from the particular type of usage or, in the case of a pressure vessel, from the contents of the vessel, either liquid or gaseous. In such case it is important that arrangements be made for the vessel to be emptied periodically and the interior inspected carefully, either by entry of the inspector into the interior or by visual evidence of the interior obtained by looking through inspection openings.

The inspector must use his best judgment in endeavoring to determine the locations of critical stresses and inspect the parts, including particularly the welds, by which those stresses are carried. In the presence of corrosive agents parts of structures that are subjected to high stress are subject to accelerated corrosion. This is particularly noticeable in pressure vessels containing corrosive liquids or gases. The effect is particularly dangerous if the deposited weld metal is porous or not properly placed to assure uniform stress distribution. Any unusual effects observed on the welds or structural members that may have a weakening effect should be carefully noted.

The inspector should also watch carefully for the deformation of parts of the structure which may result from improper loading of the structure or temporary overloading. Usually the effects of such conditions are independent of the welded attachments but unless the welded joints are prac-

tically perfect the concentrated stresses from such loadings are likely to localize at the welds. When such conditions are observed the inspector should report them immediately and recommend that the structure be taken out of service until any condition of localized weakness can be corrected.

SECTION IV—WELDING CHARACTERISTICS OF FERROUS METALS

Introduction

Since it is impossible to devise rules which will enable an inspector to identify all of the factors likely to cause defects in welds, this discussion will attempt only to describe a few of them briefly. A thorough knowledge of the limitations of a given welding process, coupled with an understanding of the conditions which are likely to promote formation of defects, will better fit the inspector to judge the probability of obtaining joints which are satisfactory for a particular service.

The difficulties arising in the production of satisfactory welded joints in ferrous metals will be separated into two major groups (1) defects likely to occur in all ferrous metals, and (2) defects or other special problems which are related to the metallurgical characteristics of the material.

This discussion applies specifically to the metal arc and gas welding processes, since they are the methods most frequently used for work subject to inspection. Space does not permit a separate discussion of the carbon arc, atomic hydrogen or other processes of welding. However, if the inspector in his training obtains a knowledge of these other processes, the information regarding the causes of defects in the metal arc and gas processes may be useful to him.

Three additional limitations will be placed on the scope of this discussion:

1. Only those materials will be considered which are known to readily permit the production of satisfactory welded joints.
2. A joint design will be considered with which, under test conditions, the process under discussion will produce a satisfactory joint.
3. An electrode or welding rod will be considered which is capable of producing sound metal and of fusing properly to the base material.

Defects Likely to Occur in All Ferrous Metals

The principal defects found in welded joints in all ferrous metals are (1) Incomplete penetration, (2) Lack of fusion, (3) Undercutting, (4) Slag inclusions, (5) Porosity and (6) Cracking.

1. Incomplete Penetration

This term is frequently applied to describe the failure for any reason of the filler metal and base metal to fuse integrally at the root of a joint or, more specifically, (1) the failure of the root face sections of a welding groove to reach the melting temperature for their entire depth, or (2) the failure of the weld metal to reach the root of a fillet joint, leaving a void caused by bridging of the weld metal from one plate to the other.

Although incomplete penetration may, in a few cases, be due to failure to dissolve or flux surface oxides and impurities, the heat transfer conditions

existing at the joint are a more frequent source of this defect. If the metal being joined first reaches the melting temperature at areas above the base of the joint, molten metal may bridge between these areas and screen off the heat source (gas flame or arc) before the metal at the root melts. In metal arc welding, the arc will establish itself between the electrode and the closest part of the base metal. All other areas of the base metal will receive heat principally by conduction. If the portion of the base metal closest to the electrode is a considerable distance from the extreme root of the joint, the conduction of heat may be insufficient to raise the metal temperature at the root to the melting point. The same principles of heat flow require that, with the gas process, the flame be so concentrated that the metal at the extreme root of the weld reaches the melting temperature before or at the same time as the metal at points farther from the root.

Incomplete penetration is a particularly undesirable condition if there is any possibility that the root of the weld may be subject to either direct tension or bending stresses. The void or unfused area permits stress concentration which may result in failure without appreciable deformation. Even though the service stresses in the structure may not involve tension or bending at this point, the shrinkage stresses and consequent distortion of the parts during welding will frequently cause a crack to initiate at the unfused section. Such cracks may progress as successive beads are deposited until they extend through almost the entire thickness of the weld.

The most frequent cause of this type of defect is a joint design not suitable for the welding process used or for conditions of actual construction. When a groove is welded from one side only, complete penetration is not likely to be obtained consistently with the metal arc process if (1) the root face dimension is too great even though the root opening is adequate, (2) the root opening is too small or (3) the included angle of a V-type groove is too small. Any of these factors will make it difficult to reproduce test results under the conditions of actual construction. If the joint design is known to be adequate, incomplete penetration may result from (1) the use of too large an electrode, (2) an excessively high rate of travel or (3) the use of insufficient welding current.

The design factors tending to produce incomplete penetration with the gas process are similar to those for the metal arc process. However, it is not generally considered good practice with this process to use joints having no root opening whether a backing strip is used or not. If the joint design is known to be adequate, incomplete penetration may result from (1) the use of an incorrect tip size, (2) too great a welding speed or (3) insufficient preheat.

2. Lack of Fusion

While this term is sometimes applied to the condition previously referred to as incomplete penetration, it is used here in a more restricted sense to describe the failure of a welding process to fuse together adjacent layers of weld metal or adjacent weld metal and base metal. This failure to obtain fusion may occur at any point in the welding groove.

Like incomplete penetration, lack of fusion is caused by (1) failure to raise the temperature of the base metal (or previously deposited weld metal) to the melting point or (2) failure to dissolve, by means of proper fluxing, the oxide or other foreign material present on the surfaces to which the deposited metal must fuse.

Lack of fusion is not a common defect in metal arc welds unless the surfaces being welded are covered with a material which prevents the molten weld metal from fusing to them. Gas welding, if performed by an inexperienced or careless operator, may yield areas of lack of fusion if sufficient heat is not supplied to the base metal (or previously deposited filler metal). Such lack of fusion will be attributable to the use of too small a tip or failure to use supplementary heating when required.

Inspectors should not infer from this brief discussion that it is necessary to melt an appreciable portion of the sidewalls of the groove in order to be certain of securing proper fusion. It is actually only necessary to bring the surface of the base metal to the fusion temperature to obtain metallurgical continuity of the base and weld metal.

Lack of fusion is best avoided by ascertaining that the surfaces to be welded are free of injurious foreign material and by the use of welding operators who have adequately demonstrated their ability to make sound welds.

3. Undercutting

This term is used to describe either (1) the burning away of the side wall of a welding groove at the edge of a layer or bead thus forming a sharp recess in the side wall in the area to which the next layer or bead must fuse, or (2) the reduction in base metal thickness at the line where the last bead is fused to the surface.

Undercutting of both types is usually due to the technique employed by the operator. However, in metal arc welding, different types of electrodes show widely varying tendencies in this respect. With some electrodes, even the most skilled operator may be unable to avoid undercutting under certain conditions. With a specific electrode, too high a current or too long an arc may increase the tendency to undercut.

Undercutting of the sidewalls of a welding groove is not a serious problem and will in no way affect the completed joint if care is taken to properly correct the condition before depositing the next bead. This is best accomplished by using a well rounded chipping tool to eliminate the sharp recess which might serve to trap slag. However, if an operator is sufficiently experienced and knows to what extent subsequent beads will penetrate, chipping is not always necessary. Undercutting at the surface of a joint should not be permitted in its aggravated forms as it may materially reduce the strength of the joint, particularly with regard to fatigue stresses. Fortunately, this type of undercutting is always readily detectable by a visual examination of the surface of the completed weld and can usually be corrected by the deposition of additional metal.

4. Slag Inclusions

This term is used to describe the metallic oxides and other solid compounds which are sometimes found as elongated or globular inclusions in welded joints.

During the deposition and subsequent solidification of weld metal, many chemical reactions occur between the metal, the air and the electrode coating materials or the gases produced by the flame. Some of the products of

these reactions are metallic compounds soluble only to a slight degree in the molten metal. Due to their lower specific gravity they tend to seek the upper surface of the molten metal unless restrained from doing so by other conditions.

In gas welding any slag inclusions that may occur will normally be caused by either insufficient or excessive welding temperatures. Too low a temperature may permit solidification to occur before the oxides on the surface of the base metal have an opportunity to float to the surface of the weld. Too high a temperature or an oxidizing flame may produce excessive quantities of oxide which will not all be removed from the weld.

When welding by the metal arc process using covered electrodes, some slag may be formed by reactions below the surface of the molten metal, slag may be forced below the surface by the stirring action of the arc or slag may flow ahead of the arc causing the metal to be deposited over it. When slag is once present in the molten metal, from any cause, it tends to rise to the surface by virtue of its lower density. Any factors such as high viscosity of the weld metal, rapid chilling or too low a temperature may prevent its release. When weld metal is deposited by the metal arc process over a sharp V-shaped recess, such as that produced by a diamond point tool, slag will frequently be found trapped in the weld. Under such conditions, the arc may fail to raise the bottom of the recess to a sufficiently high temperature for the metal to fill it and allow the slag which was ahead of the arc to float out. A similar condition exists if a sharp recess is present due to undercutting by the previous bead. Slag inclusions of this type are usually elongated, and if individual inclusions are of considerable size or are closely spaced they may reduce the strength of the joint. It is usually not desirable to remove small or isolated inclusions.

Slag forced into the metal by the arc or formed there by chemical reactions usually appears as finely divided or globular inclusions. Inclusions of this type are likely to be a particular problem in overhead welding.

The majority of slag inclusions may be prevented by proper preparation of the groove before each bead is deposited, using care to avoid leaving any contours which will be difficult to penetrate fully with the arc. Obviously, the release of slag from the molten weld metal (except in the case of position welding) will be aided by all factors which tend to make the metal less viscous or retard its solidification, such as preheating and high heat input per inch per unit time.

5. Porosity

This term is used to describe the globular voids free of any solid material which are frequently found in welds. In reality they are another form of an inclusion resulting from the chemical reactions taking place during welding. They differ from slag inclusions in that the voids contain gas rather than a solid.

The gases forming the voids are derived from (1) gas released by the cooling weld metal because of reduced solubility as the temperature drops, and (2) gases formed by chemical reactions in the weld.

The porosity normally found in metal arc welds produced by covered electrodes or in gas welds does not have a serious effect on the mechanical properties of the joint unless present in excessive quantity.

Formation of porosity is most readily prevented by avoiding (1) over-heat-

ing of the weld metal (gas process), (2) excessive currents or (3) excessive arc lengths. Too high a metal temperature increases unnecessarily the amount of gas dissolved and which will be available for release from solution upon cooling. High consumption of the deoxidizing elements of the coating may take place during deposition if excessive currents and arc lengths are used, leaving insufficient quantities available to combine with the gases in the molten metal during cooling.

6. Cracking

While cracks sometimes occur in thick sections of low tensile strength material because of small defects such as minor cases of lack of fusion, slag inclusions, etc., their tendency to form is primarily related to the metallurgical characteristics of the steel. Therefore, cracking will be discussed in detail under the following section.

Conditions Related to the Metallurgical Characteristics of the Filler and Base Metal

Separation of materials into groups having generally similar metallurgical characteristics will permit a simplified study of the effect of these characteristics upon certain conditions produced in welded joints, namely, hardness, brittleness and cracks. It will also be useful to consider certain corrective measures, such as preheating and stress relieving, which can be employed to minimize the undesirable effects of these conditions. It is important for the inspector to know under which group the steel being welded belongs.

1. Material Groups

Although an ideal separation of the ferrous metals into groups having similar responses to welding operations must await a satisfactory definition of the term weldability and the development of suitable tests to measure this property, an approximate classification will be useful for the purposes of this discussion. Accordingly, the ferrous metals will be divided into four groups: (1) low carbon steels, (2) medium carbon steels, (3) low alloy steels and (4) high alloy steels. Each of these groups will be defined as follows:

1. *Low Carbon Steels.*—Unalloyed steels having 0.30% carbon max., 0.70% manganese max. and 0.30% silicon max., or unalloyed steels complying with the formula and other limitations given for Group P Number 1 of Table 5 of the A.W.S. Standard Qualification Procedure.*
2. *Medium Carbon Steels.*—Unalloyed steels having 0.35% carbon max., 0.90% manganese max. and 0.30% silicon max., or unalloyed steels complying with the formula and limitations of Group P Number 3 of Table 5 of the A.W.S. Standard Qualification Procedure.
3. *Low Alloy Steels.*—Steels listed in Group P Number 4 of Table 5 of the A.W.S. Standard Qualification Procedure.
4. *High Alloy Steels.*—Steels containing more than 3% of alloying elements which are normally used because of superior corrosion or high-temperature oxidation resistance.

* This Table appears on pages 1013 to 1015.

2. Hardness and Brittleness

Hardness and brittleness in welded joints are metallurgical effects produced by the heat cycle of welding and are among the chief factors which tend to cause cracking. While a complete discussion of the metallurgical properties of the various metals is beyond the scope of this chapter, a rudimentary knowledge of the tendency of the various groups of materials to harden or become brittle will be of value to the inspector.

It can be said of the first three groups that the hardness and, roughly speaking, the ability of the materials to deform without rupture will depend upon the group to which they belong, i.e., low carbon, medium carbon or low alloy, and also the rate at which they cool from the elevated temperatures produced by the welding operation. The rate of cooling will obviously depend upon a number of physical factors such as (1) the temperature of the base metal, (2) the thickness and thermal conductivity of the base metal, (3) the heat input per unit time at a given section of the weld and (4) the atmospheric temperature. With a given cooling rate the materials in the low carbon steel group will harden considerably less than those of the medium carbon group. The low alloy steels included in the third group will exhibit a wider variation in their hardening characteristics and some of them may be similar to the low carbon group while others will react like the medium carbon group.

The high alloys must necessarily be given separate consideration since this group includes the so-called martensitic steels which behave similarly to the medium carbon and low-alloy groups except that they harden to a greater degree with a given cooling rate, and also includes the austenitic and ferritic stainless steels. Neither the austenitic steels, of which the common 18% chromium–8% nickel stainless steel is an example, nor the ferritic steels, of which the low carbon straight chromium steels (or irons) containing 18% or more of chromium are an example, harden upon quenching from elevated temperatures. However, the ferritic steels in general are rendered brittle (but not hard) by welding operations.

3. Cracking

Cracking of welded joints results from the presence of localized stress which at some point exceeds the ultimate strength of the material. When cracks occur during, or as a result of, welding, little deformation is usually apparent.

It is well known that materials which will exhibit considerable ductility when subjected to uniaxial stress may, when subjected to two- or three-dimensional stresses, fail without appreciable deformation. Shrinkage caused by welding operations frequently sets up multi-directional stress systems. If because of such stresses a joint, or any portion of it, is incapable of sustaining appreciable deformation without failure, additional stresses set up in deposition of subsequent layers or in the welding of other joints may force this part to deform and cause failure.

Cracks in welded joints which appear during welding are rarely caused by multi-directional stresses alone. However, experience has indicated that even though such stresses do not cause cracking, they may, particularly in the case of heavy or complicated structures, cause failure to occur with little deformation when additional load is applied. To avoid this

undesirable condition, stress relieving is usually specified for important structures fabricated of heavy material.

An unfused area at the root of a butt joint may result in cracks without appreciable deformation if this area is subjected to tensile stress. In welding two plates together the root of the joint is subject to such a tensile stress as successive layers are deposited, and, as already stated, a partially fused root will frequently permit a crack to start which may progress through practically the entire thickness of the weld.

After a welded joint has become cold, cracking is more likely to occur if the metal is either hard or brittle. Obviously, a ductile material will withstand multi-directional stresses and stress concentrations which would cause a hard or brittle material to fail.

4. Heat-Treating Operations

Of the various heat-treating operations, preheating and stress relieving are those most frequently employed to reduce the tendency of welded joints to fail by cracking.

Preheating reduces the temperature difference between the base metal and the filler metal which, to some degree, decreases the magnitude of the shrinkage stresses caused by the contraction of the weld. In the case of heavy sections or of materials that become brittle due to the heat cycle of the welding operation, this reduction in shrinkage stresses may be of considerable importance in preventing cracking. Steels in the low carbon group require preheating only under special conditions. With the medium carbon and many of the steels in the low-alloy group, preheating is highly desirable, and with the martensitic high alloys it is likely to be absolutely essential to the production of joints free of cracks. If a sufficiently high temperature is used, preheating may also reduce the final hardness obtained in the welded joint. However, in order to accomplish this, the preheating operation must reduce the cooling rate of the weld and adjacent base metal sufficiently to minimize, or eliminate entirely, the formation of martensite (the hard brittle constituent obtained upon rapid cooling of many carbon and alloy steels from an elevated temperature).

In the case of steels which harden upon welding, stress relieving performs a dual function: first, it relieves the residual stresses produced by welding, and second, it softens the weld and adjacent base metal and restores its ductility. While preheating is primarily effective in preventing cracks during the welding operation, stress relieving is effective in reducing the occurrence of brittle fractures after completion of the weld or in service.

SECTION V—WELDING CHARACTERISTICS OF NON-FERROUS METALS

Copper and Copper Alloys

The inspector should be familiar generally with the welding of copper and copper alloys, methods of qualifying welding procedures and operators and methods of testing welds. He should also be familiar with the specifications or codes governing the particular work which he is to inspect. Some of the things to be observed in carrying out the inspection are the following:

Appearance of Weld.—The weld should have a neat appearance, be uniform in width and in height and contour of reinforcement. A localized increase in width of weld may mean excess heat at that point or an improper repair—a covering up of a leak instead of gouging and rewelding.

Whenever possible, the inspector should examine the underside of a butt weld for correct penetration. Where too much metal has sagged through the joint (no back up) particular inspection should be given for a distance of approximately 2 in. each side of the icicle. Usually radial gas holes are present (particularly true with silicon bronze). The amount of sagging should not exceed $^{3}/_{16}$ in.

Undue distortion of the plates may mean improper jigging or indicate locked-up stress or relief of same.

Undercutting, Cold Laps.—As copper and high copper alloys are very fluid at fusion-welding temperatures, there is some danger that the vertical face of an arc fillet weld may be undercut and undercutting may also occur on the far side of a vertical gas butt weld. Cold laps may occur on the front edges of a vertical butt or fillet weld and on the lower surface of a horizontal gas or arc fillet weld.

Cracks, Unsoundness.—As in ferrous metals, internal cracks and unsoundness will be spotted most effectively with the X-ray. However, the inspector can generally detect any serious defect of this character. Cracks coming to the surface can generally be spotted. A 7- or 10-power hand magnifying glass is a distinct aid in such inspection. Where there is any doubt a chip taken with a round nose chisel driven along the center line of the supposed crack will decide. If the chip separates like a ram's horn, the crack is proved while if it holds together there is no crack.

A similar test at the edge of the weld will prove correct or inadequate fusion.

Cracks may sometimes be spotted by the kerosene-chalk test. This test is made by flooding the surface suspected of having cracks, with kerosene. After removing the surplus kerosene the surface is covered with a mixture of chalk powder in water or whitewash. After this is dried the kerosene in the cracks will be absorbed by the chalk and become evident because of the consequent discoloration. This test should be undertaken only by one who is familiar with the technique of carrying it out properly.

The gouging chisel is also useful in proving or disproving gas porosity. If there is any suspicion of unsoundness from a close inspection of the surface, a chip may be taken and the chipped surface inspected as well as the fracture at the end of the chip for porosity.

If any cracks or unsoundness be discovered in a weld in a pressure vessel, the same should be chipped out and rewelded. Weeps in copper alloys do not corrode tight as is often the case in ferrous welds. Caulking is also unsatisfactory in closing up minute porosity in copper or copper alloys.

Oxidized Weld Metal.—A heavy black scale on the weld surface may indicate undue exposure of the metal at high temperature. Oxide in the metal is usually indicated by brittleness in the weld metal. It is rarely found in copper-silicon or copper-zinc alloys but may occur in arc-welded copper mostly in the top of the bead or in gas-welded electrolytic copper in a narrow zone at the edge of the weld. It may occur in phosphor bronze or the cupro-nickels if there is an inadequacy of the deoxidizer in the filler rod, and in aluminum bronze it may occur as a thin web which interrupts the continuity of the fused metal.

In any case, the oxidized metal can usually be spotted by chipping the location and noting the ductility as indicated by the chip. Oxidized metal will break off short while clean metal will show a reasonable degree of ductility.

Entrapped flux will usually occur, if at all, in the area at the edge of the weld. It can be discovered only by chipping or with the X-ray.

In the case of silver brazed or soft soldered copper or brass tube in wrought copper or cast brass fittings, the inspector will have to decide from the appearance of the metal and the solder fillet as to whether the job has had the correct temperature.

In butt-welded or bell-and-spigot brazed (bronze-welded) brass or copper pipe, the appearance of the weld is usually sufficient evidence of a workmanlike job though the inspector can spot "icicles" under the butt joint only by looking or feeling inside the pipe.

Aluminum and Aluminum Alloys

External Inspection—Visual.—Fusion welds in aluminum alloys are inspected visually with or without low magnification for cracks, penetration, undercutting, size of reinforcement and flux removal. Remarks under Copper and Copper Alloys relating to these several items also apply here.

Internal Inspection.—X-ray examination of fusion welds in the aluminum alloys can be accomplished to show porosity, lack of penetration, voids and other non-uniformity in the weld structure with the exception that oxide films do not appear clearly. In view of the fact that oxide films may be included in a weld if incorrect technique is used in making the joint, and may substantially reduce the strength, it follows that X-ray examination should be coordinated with additional tests made by trepanned plugs or nick break tests on welded prolongs or cut-outs from the joints. Microscopic or visual examination of the weld structure on these specimens will show up oxide inclusions.

Mechanical Tests.—In many applications, liquid or gas-tightness of the joints is essential and a proof test on the design assumptions desirable. In such cases pneumatic pressure tests are applied where pressures up to 8 pounds per square inch will provide an adequate test on vessels smaller than 100 gallons. Liquid-tightness is established by immersing the part in water or painting the joints with a light oil or a soap suds mixture. For higher pressures and larger vessels hydrostatic pressure tests are advisable.

In addition to pressure tests the tensile strength of reduced-section specimens, elongation, free-bend and nick-break tests are sometimes made on welded prolongs or cut-outs from the welds. Such tests are not usually conducted except in special cases.

Repairs.—Repairs to fusion welds, where cracks, undercutting and lack of penetration are concerned, should be made by chipping out the defective area and rewelding. Lack of sufficient reinforcement can be repaired merely by rewelding. Where low pressures are concerned small leaks in welds in commercially pure aluminum and aluminum-manganese plate are frequently stopped by peening. In addition to being the most economical this method does not introduce distortion, which may occur from making welded repairs.

Another method of importance when welding aluminum castings con-

cerns the impregnation of the casting under pressure with sodium silicate or a phenolic resin. In most cases chipping and rewelding castings which show seepage leaks will merely extend the leaking area. Repair operations, consequently, are made by a sealing operation rather than a rewelding operation.

Nickel and Nickel Alloys

In general, all information contained in the foregoing parts of this report, dealing with Inspection and Testing of Welded Structures, Materials, Fabrication, Welding, Examination of Welds, Stress Relieving, Hydrostatic Test, Final Inspection and Check, Field Inspections, and Defects Likely to Occur in All Ferrous Metals, applies with equal force to the inspection of structures and equipment fabricated of nickel, monel or other high-nickel alloys. (See Chapter 24.)

Visual Inspection.—Fusion welds are inspected visually with or without low magnification for cracks, undercutting, penetration, size of reinforcement and flux removal.

X-ray Inspection.—X-ray examination of fusion welds in nickel and nickel alloys will disclose soundness, degree of penetration, slag inclusions and uniformity of weld structure. The defects which are found should be removed by chipping and rewelding. The same standards that are used for steel may be used for judging nickel and high-nickel alloys.

Mechanical Tests.—The usual tensile, free- or jig-bend, nick-break or other mechanical tests may be made as required. Pressure tests of vessels are made using air or water as the circumstances dictate.

Repairs.—Defects in welds should be removed by chipping and rewelded. Peening is not an effective method of repairing leaks in nickel or nickel-copper alloys.

SECTION VI—ETCHING REAGENTS

This section lists a number of etching solutions suitable for carbon and low-alloy steels as well as for the more common non-ferrous metals and alloys. The manner of applying the solutions is indicated.

To preserve the appearance of the etched specimens they should, after etching, be washed in clear water, the excess water removed, then immersed in ethyl alcohol and dried. The etched surface may then be preserved by coating with a thin clear lacquer.

Etching Reagents for Carbon and Low Alloy Steels

Hydrochloric Acid.—Hydrochloric (muriatic) acid and water equal parts by volume. The solution should be kept at or near the boiling temperature during the etching process. The specimens should be immersed in the solution for a sufficient period of time to reveal all lack of soundness that might exist at the cross-sectional surfaces.

Ammonium Persulphate.—One part of ammonium persulphate to nine parts of water by weight. The solution should be used at room temperature and should be applied by vigorously rubbing the surface to be etched with a piece of cotton saturated with the solution. The etching process should be continued until there is a clear definition of the structure of the weld.

Iodine and Potassium Iodide.—One part of powdered iodine (solid form), two parts of powdered potassium iodide and ten parts of water, all by weight. The solution should be used at room temperature and brushed on the surface to be etched until there is a clear definition or outline of the weld.

Nitric Acid.—One part of nitric acid and three parts of water by volume. (*Caution:* Always pour the acid into the water. Nitric acid causes bad stains and severe burns.) The solution may be used at room temperature and applied to the surface to be etched with a glass stirring rod. The specimens may also be placed in a boiling solution of the acid but the work should be done in a well ventilated room. The etching process should be continued for a sufficient period of time to reveal all lack of soundness that might exist at the cross-sectional surfaces.

Etching Reagents for Non-Ferrous Metals and Alloys

Chromium-Nickel Alloys.—Hydrochloric (muriatic) acid and water equal parts by volume. The solution should be used at a temperature of approximately 160°F. Another reagent uses 2 parts of concentrated sulphuric acid, 1 part of concentrated hydrochloric acid and 3 parts of water, by volume. This solution should be used warm.

Copper and Copper Alloys.—A 25 to 50% solution of nitric acid. The solution should be used cold but it will heat up as used. The etched part should afterward be dipped in a one-to-one solution of concentrated hydrochloric acid and water.

Aluminum and Aluminum Alloys.—Ten parts of hydrofluoric acid, 15 parts of hydrochloric acid and 90 parts of water. The solution should be used at room temperature. The specimen should be immersed in the solution for 15 to 20 seconds, washed in warm water and then dipped in concentrated nitric acid.

Monel.—Equal parts by volume of water and concentrated nitric acid. The solution should be used at room temperature. The specimen should be immersed for 5 to 10 seconds or for a sufficient period to produce a clear definition of the structure of the weld.

Nickel.—Concentrated nitric acid. The specimen should be immersed in the solution at room temperature until there is a clear definition of the structure of the weld.

Inconel.—Aqua regia. The solution should be used warm. The specimen should be first warmed in hot water and then immersed in the solution until there is a clear definition of the structure of the weld. If the weld does not etch readily a small amount of cupric chloride may be added to the solution.

CHAPTER 31

SAFE PRACTICES IN WELDING AND CUTTING*

Fire Protection, Eye Protection, Clothing, Health Hazards and Ventilation, Special Precautions.

IT IS not intended that this chapter go into the question of what structures can be safely welded beyond stating that where the safety of a structure is dependent upon the strength of the welded joint, the welding should be carried out under the provisions of the Code that applies and the procedure and operators doing the work qualified in accordance with the provisions of the particular code.

The handling and storage of equipment and supplies used in electric welding, thermit welding and gas welding and cutting require that the user familiarize himself with and observe certain safe practices. For detailed good practices, the reader is referred to National Safety Council Pamphlets Nos. 23 and 105, respectively, entitled "Gas Welding and Cutting" and "Electric Welding." Manufacturers also furnish instructions with their equipment and supplies with which the user should be conversant.

As the above-mentioned literature amply covers proper practices in handling and storage, this chapter will be confined to an enumeration and discussion of possible hazards in the application of the processes.

Fire Protection

The tremendous increase in the amount of welding and cutting equipment in use during the past ten years or so has resulted in an increase in the frequency of fires involving the use of the processes. While the severity rate has not been unduly alarming, it must be remembered that every small fire is a potential big fire and that the carelessness that is usually responsible for the fire should not be tolerated.

Certain definite rules for the prevention of fires when welding and cutting have been formulated. These rules are:

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* Prepared by a committee consisting of H. S. Smith, Union Carbide Co., *Chairman;* J. I. Banash, Consulting Engineer; J. H. Deppeler, Metal & Thermit Corp.

1. Do not perform cutting or welding work where an open flame or arc would be dangerous, as in or near rooms containing flammable vapors or liquids, or exposed loose combustible material.

2. Be sure that cutting and welding equipment is not used near dipping or spraying rooms, or rooms containing loose readily combustible material unless there is no possibility of the vapors or sparks and molten metal passing through broken or open windows, open doorways, or cracks or holes in walls or floors.

3. If the work can be moved it is far preferable to take it to a safe place for cutting and welding than to perform the work in a hazardous location.

4. Where welding or cutting has to be done in the vicinity of combustible material, special precautions should be taken to make certain that sparks or hot slag—from cutting operations particularly—do not reach combustible material and thus start a fire. If the work cannot be moved, exposed combustible material should, if possible, be moved a safe distance away. Sweep floors clean and, if combustible, wet them down before starting work. Wooden floors should preferably be covered with metal or other suitable non-combustible material where sparks or hot metal are likely to fall. Wherever there are floor openings or cracks in the flooring, make certain that there are no highly combustible materials on the floor below, where they would be exposed to hot metal or slag which might drop through the floor. Particular attention should be taken to see that hot slag or sparks do not fall into machine tool pits.

5. Observe the same precautions outlined in Rule 4 with regard to cracks or holes in walls, open doorways and open or broken windows. Use sheet metal guards or asbestos curtains where needed. Make sure that the guards and curtains are adequate. Because hot slag may roll along the floor for considerable distances, it is important when using asbestos blankets as a curtain that no openings exist where the curtain meets the floor.

6. When it is necessary to do welding or cutting close to wooden construction or in locations where combustible material cannot be removed or protected, small hose, chemical extinguishers, or fire pails should be conveniently at hand.

7. Whenever combustible material has been exposed to molten metal or hot slag from cutting operations, a man should be kept at the source of the work for a half hour after completion, to make sure that smouldering fires have not been started.

8. When electric welding processes are being employed all the usual precautions in handling electric power must be observed. Short circuits or excessive heating with their attendant fire and injury hazard may result from placing metallic objects near electric welding sets, by dragging the welding leads across sharp corners of steel plates, or the like, and thus cutting through the insulation; by using leads too small to carry the necessary current and thus burning off the insulation; by throwing down electrode holder carelessly, and by the breaking of electric connections. All electrical installations should comply with the provisions of the National Electrical Code.

9. All gas welding and cutting equipment should be kept in good order. Use good hose and renew it when necessary. When hose is worn near the couplings, cut off a few inches and renew the connections, making sure that

they are tight. Good connections between regulators and cylinder valves are important. Blowpipes should never be hung from regulators or across the tops of cylinders. Only cylinders which comply with Interstate Commerce Commission shipping container specifications and equipped with safety devices approved as to type and location shall be used for all compressed gases. For the installation and operation of gas systems for welding and cutting the regulations of the National Board of Fire Underwriters as recommended by the N. F. P. A. should be followed. The reader is also referred to "Safe Practices for Installation and Operation of Oxy-Acetylene Welding and Cutting Equipment" issued by International Acetylene Association.

10. In thermit welding the mold should be thoroughly dried before the charge is lighted. The crucible should always be provided with a cover. When the charge has been ignited the operator should stand a few steps away and should wear goggles. Painful burns may occur from the metal splashings, by upsetting the crucible, by the breaking of the mold, or by allowing the molten steel to come into contact with moisture in the mold or on the floor or ground. Slight injuries may occur from taking hold of the apparatus or welded parts before they are cool.

Eye Protection

In welding or cutting applications it is very important that the eyes be protected from the heat and glare of the flame or arc, and from the particles of hot metal that may fly up from the work. Properly designed and colored lens fitted in suitable goggles will furnish adequate protection to the eyes of gas welding and cutting operators. In electric arc welding utilizing current of 30 amp. or more, it is necessary for operators to be equipped with shields or helmets that will protect not only the eyes but the skin because of the intensity of the ultra-violet and infra-red rays. The choice of proper eye-protection equipment should be made by a responsible person who fully understands what it should consist of, and he should be guided by the specifications as detailed in "National Safety Code for the Protection of the Heads and Eyes of Industrial Workers" issued by the National Bureau of Standards, Washington, D. C. This booklet provides proper specifications for eye protection for operators of the various welding and cutting processes. It should be noted that special precautions must be taken to protect other workers or passers-by from the harmful rays given off in arc welding operations. It is preferable to locate such jobs in special rooms. If this is impracticable the operation should be screened or enclosed not only to prevent workers or passers-by from looking directly at the arc, but also to protect them from reflected rays as much as possible. Further protection against reflected rays is frequently provided by applying paint to the screen or enclosure and to other near-by surfaces. Zinc oxide combined with lampblack to produce a blue-gray color is satisfactory. Goggles suitable for other forms of welding are satisfactory for thermit welding. Welding operators should wear suitable goggles to protect the eyes when removing slag from welds and when chipping and grinding welds. For helpers and others who must work in the vicinity of heavy arc-welding operations, goggles are recommended if screen protection or the like is not provided.

Clothing

Obviously when working with a flame, arc or molten metal, clothing should be of such nature that the possibility of its catching fire is reduced to a minimum. Woolen clothing is preferable to cotton because it is not readily ignited and because it helps protect the operator from changes in temperature. Outer clothing such as jumpers and overalls should be free from oil or grease.

As sparks, hot slag or hot metal may lodge in rolled-up sleeves, in pockets or in the cuffs of overalls or trousers, it is highly desirable that sleeves and collars be kept buttoned and that pockets be eliminated from the front of overalls and aprons. Low shoes with unprotected tops are not desirable.

Health Hazards and Ventilation

The actual health hazards from welding and cutting operations are relatively few, usually easily identified, and can be controlled. A great variety of health hazards have been mentioned in recent years, but these are often quite theoretical. If the well-recognized hazards are controlled, the rest do not exist.

The hazards to health arise from the gases, fumes or dust which may be present because of the materials needed for or produced during welding, or the material being welded, including coatings. Harm results from contamination of the air and can be avoided by proper ventilation. Welding in the open, or in very large shops, seldom calls for special ventilation. In smaller shops ventilating equipment may be needed and for work in small, closely confined spaces, as in tanks, and in the holds of ships, very definite steps must be taken to insure proper conditions. Conditions vary so much in different locations and with different materials that it would be very difficult to establish fair standards for ventilation based on rate of air change, concentration of fume in milligrams per cubic meter, or other standard of measurement. Ventilation at the rate of 100 cu. ft. per minute per operator should be sufficient for most work. In general, it may be said that ventilation must be sufficient to insure good visibility and a comfortable working temperature. If these are obtained no serious health hazard is likely.

Health hazards due to the base metal are usually incident to the presence of lead, cadmium and zinc.

Lead is a hazard when welding or cutting material which may have been heavily coated with lead paint, or material containing lead. Lead occurring as an impurity in brass, bronze or zinc would seldom present a hazard. Lead poisoning in welding operators has been almost entirely from exposures in the cutting of materials heavily coated with lead paint, as may be the case in scrapping of railroad cars, ships or structural iron work. The Bureau of Mines has approved a special type of filter mask for protection from lead fume under certain conditions, but airline masks are recommended as the most positive protection under all conditions.

The fumes of cadmium are occasionally encountered, as in the welding of cadmium-coated material, and may cause serious congestion or edema of the

lungs if inhaled in high concentration or for long periods. The same protective measures are advised as for lead fumes.

Zinc fumes are probably the commonest source of trouble. Metal fume fever, commonly called "zinc chills," may follow exposure to zinc fumes resulting from welding operations on galvanized material, brass or bronze, and at times from the use of bronze filler rods. They are well known in brass and bronze foundries. It should be emphasized that this condition, though annoying, does not represent a serious health menace such as lead poisoning. Metal fume fever is an acute, self-limiting condition without known complications, after-effects or chronic form. An attack usually comes on after the day's work, seldom lasts as much as twenty-four hours, and does not usually recur on repeated exposure unless there has been an interval of at least several days between exposures. Operations involving repeated production of zinc fumes require ventilation with removal of excess fumes. This often calls for local exhaust ventilation. For occasional exposure a proper type of filter respirator may give adequate protection.

Fluxes containing fluorides, such as are often used in welding of aluminum or stainless steel alloys, may produce a fume which is very irritating to the respiratory tract. The action is that of a local irritant, but concentrated fumes may lead to severe congestion. Other elements may form irritating fumes. For operations in confined spaces, local exhaust ventilation for the removal of the fume is essential.

Other fumes may be encountered from time to time, not due to any materials connected with the welding process itself but due to the heating of various residues, sludges, etc., which might be present on the material. These usually are hazardous only in very confined spaces, as in tanks. In such locations, surfaces to be welded should be well cleaned and local exhaust or other ventilation provided to insure removal of the fume.

The only toxic gases produced in welding and cutting which need be considered are carbon monoxide and the oxides of nitrogen, often referred to as "nitrous fumes." Others have been mentioned, especially impurities said to be present in acetylene gas. Such other gases or their impurities, if present at all, are in such extremely low concentrations as to present no hazard. Carbon monoxide is formed as a result of imperfect combustion, and has seldom been found in connection with welding operations. If produced it is generally for brief periods by the contact of the heat source with large masses of cold metal and in concentrations too small to be a hazard.

Oxides of nitrogen may be formed under some conditions by the action of heat on the nitrogen in the air. The action is easily reversible, and the gas formed very unstable. Under ordinary conditions no oxides of nitrogen will be formed in the air breathed by a welding operator. Under unusual circumstances in very closely confined spaces, a few cases have been reported where a harmful concentration was built up in very closely confined spaces.

With the exception of the lead hazard in work on lead-coated material and the far less serious hazard from zinc fumes, the only important health hazards in welding are due to operations in small, closely confined spaces, and can be avoided by proper ventilation or individual respiratory protective equipment. Ventilation must be directed at the removal of the fumes

and gases, and in confined spaces this means local exhaust or forced air ventilation. This should be sufficient to insure good visibility for the work, and to keep the temperature down to a point of reasonable comfort. Under such conditions there will be few, if any, health hazards. Oxygen must not be used for ventilation purposes as increased concentrations of oxygen in air cause combustible material such as clothing to burn more rapidly.

Special Precautions

It is obvious that welding or cutting or hot work of any kind should not be performed on containers that have held combustible liquids or vapors until the container has been thoroughly purged of such liquids or vapors. (See AMERICAN WELDING SOCIETY Recommended Procedure to Be Followed in Preparing for Welding or Cutting Certain Types of Containers Which Have Held Combustibles.) Jacketed vessels or tanks, containers or cored or other hollow parts should be vented before an attempt is made to preheat, weld or flame-cut same. A metal part which is suspiciously light is hollow inside and an opening should be drilled before heating; otherwise the air inside the hollow space will be expanded to the extent that violent rupture may occur.

CHAPTER 32A

WELDED JOINTS*

THERE are four fundamental types of non-pressure welds, namely, the bead, the fillet, the groove and the plug. These are illustrated in Fig. 1. Each of these fundamental types has many variations. A few of the different types of groove welds are illustrated in Fig. 3. These grooves are not necessarily intended to be exactly as shown; they are merely representative of good practice. The proportions can be varied as desired by the individ-

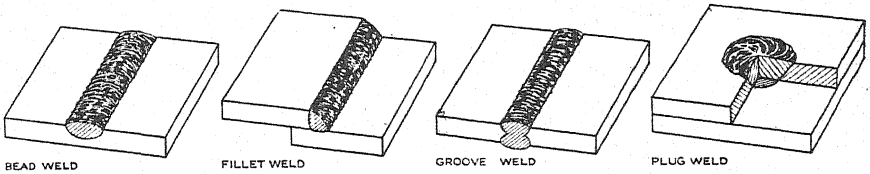


Fig. 1—Fundamental Types of Non-Pressure Welds

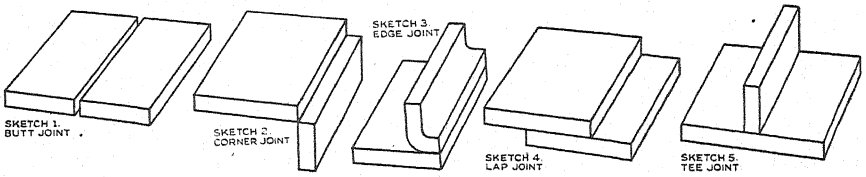


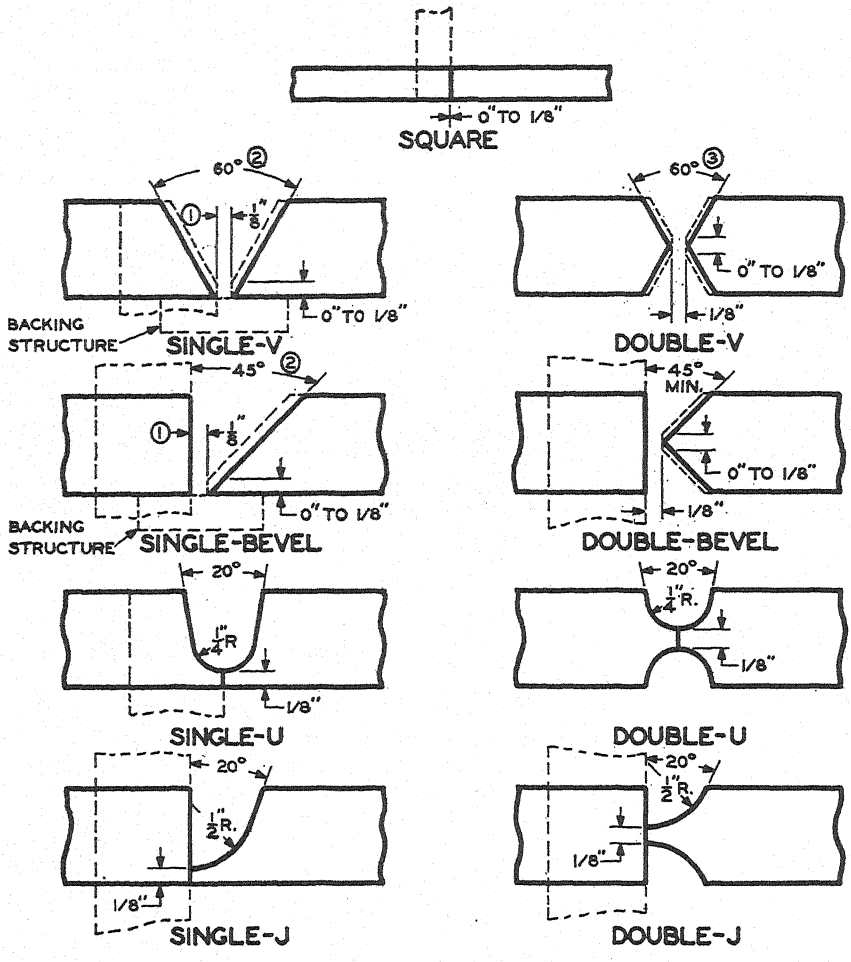
Fig. 2—Fundamental Types of Joints

ual user. The square, the single-V and the single-bevel groove joints can be used with backing structure or not, as desired, and the single-V and double-V and single-bevel and double-bevel groove joints can be used with or without root faces as desired.

There are five fundamental types of joints, namely, the butt, the corner, the edge, the lap and the tee. These are illustrated in Fig. 2. Most of the

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* Prepared by a committee consisting of Leon C. Bibber, Carnegie-Illinois Steel Corp., *Chairman;* T. W. Greene, The Linde Air Products Co.; H. O. Hill, Bethlehem Steel Co.; C. H. Jennings, Westinghouse Elec. & Mfg. Co.; Cyril Jensen, Lehigh University; A. N. Kugler, Air Reduction Sales Co.; C. E. Loos, Carnegie-Illinois Steel Corp.; A. J. Moses, Combustion Eng. Co.; Matt Wigton, Bastian-Blessing Company.



① 1/8" MIN., WITH BACKING STRUCTURE.
② MAY BE LESS WITH BACKING STRUCTURE AND WIDER ROOT OPENING.
③ MAY BE LESS WITH WIDER ROOT OPENING.

Fig. 3—Commonly Used Proportions of Grooves for Welds

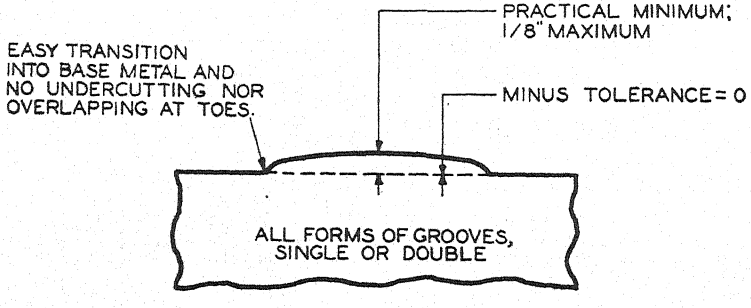
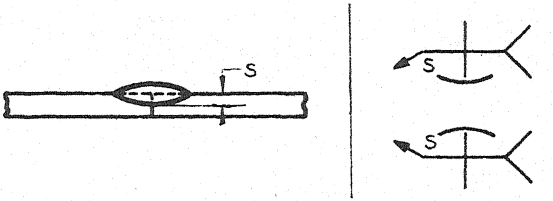


Fig. 4—Suggested Form of Reinforcement

welds can be used in various combinations to weld most of the joints. It can thus be seen that many hundreds of different types of welded joints can result from the combinations of the different welds and joints. A number of these actual joints are shown in the succeeding pages and the advantages and disadvantages of each accompany the sketches.

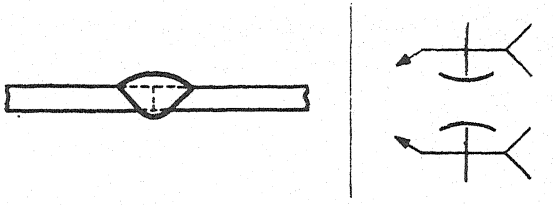
SQUARE-BUTT JOINT WELDED ONE SIDE INCOMPLETE PENETRATION



Joint 1

(a) Simplest form of joint.
(b) Efficiency low.
(c) Not suitable for fatigue or impact.
(d) Should not be used when bending tension can come on root of weld.

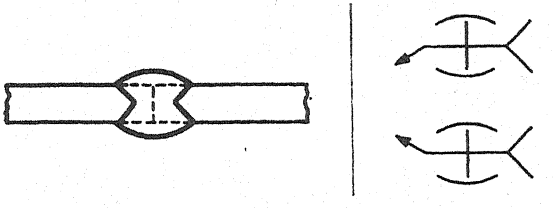
SQUARE-BUTT JOINT. WELDED ONE SIDE.



Joint 2

(a) Complete penetration can be obtained on very thin materials, about $^1/_8$ in. maximum.
(b) Efficiency in static tension is dependent on degree of penetration.
(c) If complete, fairly high efficiency obtainable.
(d) Not advisable to use in severe fatigue and impact or with bending tension on root.

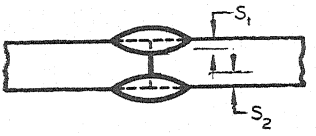
SQUARE-BUTT JOINT. WELDED BOTH SIDES.

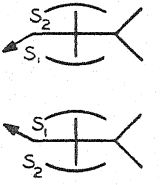


Joint 3

(a) Complete penetration can be obtained on thin materials, about $^3/_{16}$ in. maximum. Possibility of obtaining complete penetration should be checked before using this joint on important structures.
(b) High efficiencies obtainable.
(c) Should not be used for fatigue or impact unless in very thin material where complete penetration can be assured.

SQUARE-BUTT JOINT. WELDED BOTH SIDES. INCOMPLETE PENETRATION.

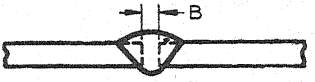


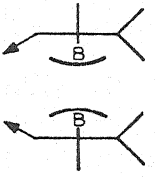


Joint 4

(a) Relatively low efficiency in static loading.
(b) Should not be used in fatigue or impact.

OPEN, SQUARE-BUTT JOINT. WELDED ONE SIDE.

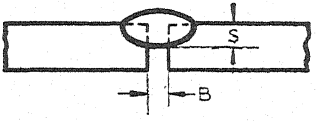


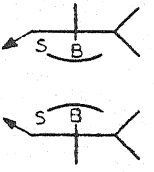


Joint 5

(a) Complete penetration possible in relatively thin materials, about $^3/_{16}$ in. maximum.
(b) Relatively high efficiencies obtainable in thin material.
(c) Should not be used in severe fatigue or impact.
(d) Should not be used when bending tension can occur in root of weld.

OPEN, SQUARE-BUTT JOINT. WELDED ONE SIDE. INCOMPLETE PENETRATION.

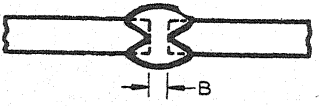


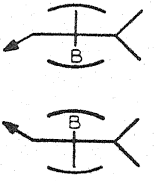


Joint 6

(a) Greater penetration possible than in the case of Joint 1.
(b) Low efficiency in static loading.
(c) Should not be used in fatigue or impact.
(d) Should not be used when bending tension can come in root of weld.

OPEN, SQUARE-BUTT JOINT. WELDED BOTH SIDES.



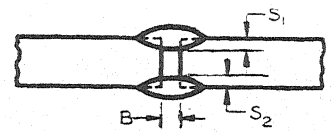


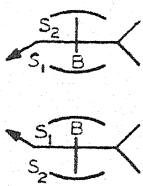
Joint 7

(a) Complete penetration can be obtained in moderately thin plate, about $^1/_4$ in. maximum.

(b) Relatively high efficiencies can be obtained if complete penetration is assured.
(c) Should not be used for severe fatigue and impact because of likelihood of flaws at root of weld.

OPEN, SQUARE-BUTT JOINT WELDED BOTH SIDES. INCOMPLETE PENETRATION



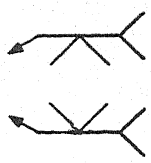


Joint 8

(a) Relatively low efficiency in static loading dependent on ratio of weld throat to plate thickness.
(b) Should not be used in fatigue or impact.

SINGLE-V, BUTT JOINT. WELDED ONE SIDE

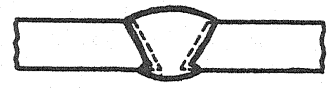


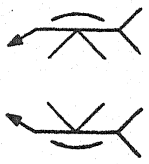


Joint 9

(a) Relatively high static efficiency obtainable.
(b) Should not be used when bending tension can exist at root of weld.
(c) Undesirable in fatigue or impact.
(d) Economical in moderate thicknesses of plating, about $^5/_8$ in. maximum.
(e) Better efficiency and production in arc welding can be obtained when backing structure is used.

SINGLE-V, BUTT JOINT. WELDED BOTH SIDES.

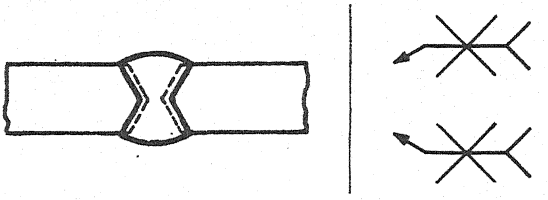




Joint 10

(a) High static efficiencies obtainable.
(b) Economical in moderate thicknesses, about $^5/_8$ in. maximum.
(c) If root is chipped or good root penetration otherwise secured, good efficiency can be obtained in fatigue or impact; better if reinforcements are removed.

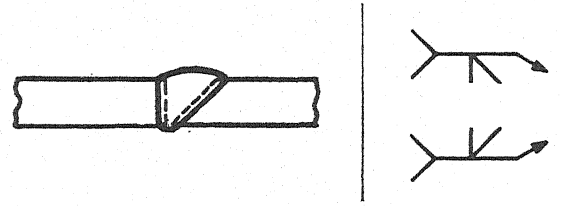
DOUBLE-V, BUTT JOINT.



Joint 11

(a) High static efficiencies obtainable.
(b) Economical in intermediate thicknesses of plating, about $1^3/_4$ in. maximum.
(c) Chipping of root difficult.
(d) If root is chipped or good root penetration otherwise secured, good efficiency can be obtained in fatigue or impact; better if reinforcements are removed.

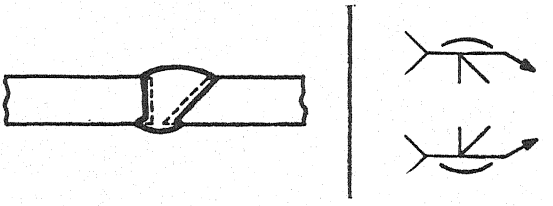
SINGLE-BEVEL, BUTT JOINT. WELDED ONE SIDE.



Joint 12

(a) Relatively high static efficiencies obtainable.
(b) One member only need be beveled.
(c) Should not be used when bending tension can exist at root of weld.
(d) Undesirable in fatigue or impact.
(e) Economical in moderate thicknesses of plating, about $^5/_8$ in. maximum.
(f) Better efficiency and production in arc welding can be obtained when backing structure is used.

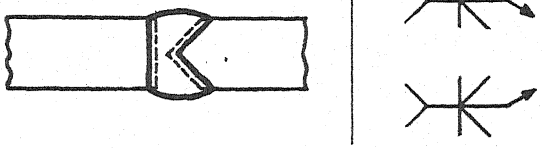
SINGLE-BEVEL, BUTT JOINT. WELDED BOTH SIDES.



Joint 13

(a) High static efficiencies obtainable.
(b) Economical in moderate thicknesses, about $^5/_8$ maximum.
(c) One member only need be beveled.
(d) If root is chipped or good root penetration otherwise secured, good efficiency can be obtained in fatigue or impact; better if reinforcements are removed.

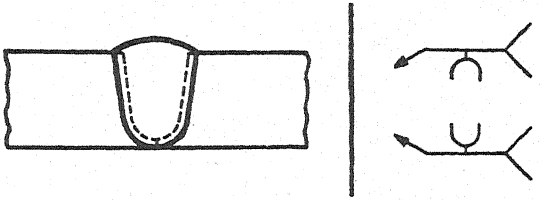
DOUBLE-BEVEL, BUTT JOINT.



Joint 14

(a) High static efficiencies obtainable.
(b) Economical in intermediate thicknesses of plate, about 1 in. maximum.
(c) Chipping of root very difficult.
(d) One member only need be beveled.
(e) If root is chipped or good root penetration otherwise secured, good efficiency can be obtained in fatigue or impact; better if reinforcements are removed.

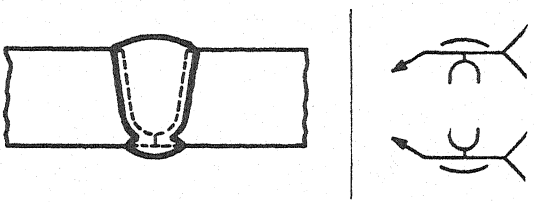
SINGLE-U, BUTT JOINT. WELDED ONE SIDE



Joint 15

(a) High efficiency obtainable.
(b) Economical from moderate thicknesses, about $1/2$ in., upward.
(c) Undesirable in severe fatigue or impact.
(d) Undesirable when bending tension can come on root of weld.

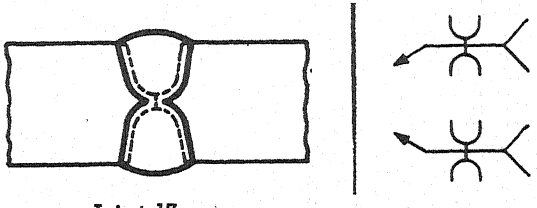
SINGLE-U, BUTT JOINT WELDED BOTH SIDES.



Joint 16

(a) Highest static efficiencies obtainable.
(b) Economical from moderate thicknesses, about $1/2$ in., upward.
(c) Chipping of root easy.
(d) Root faces facilitate assembly and prevent closing of joint during welding.
(e) If root is chipped or good penetration otherwise secured, high efficiencies can be obtained in fatigue and impact; higher if reinforcements are removed.

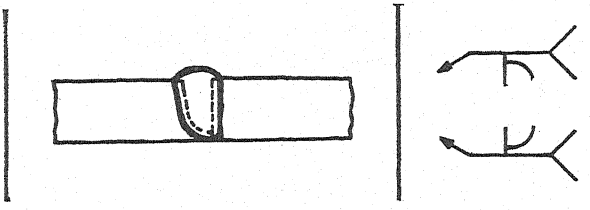
DOUBLE-U, BUTT JOINT.



Joint 17

(a) Highest static efficiencies obtainable.
(b) Most economical in the heaviest thicknesses.
(c) May be symmetrical about center line or asymmetrical as desired.
(d) Chipping of root relatively easy.
(e) Root faces facilitate assembly and prevent closing of joint during welding.
(f) If root is chipped or good penetration otherwise secured, high efficiencies can be obtained in fatigue and impact; higher if reinforcements are removed.

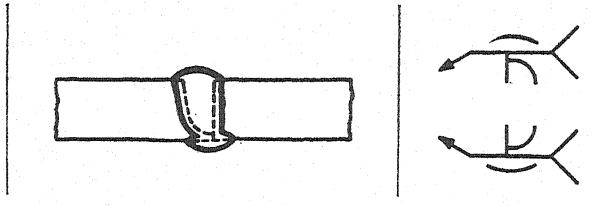
SINGLE-J, BUTT JOINT. WELDED ONE SIDE



Joint 18

(a) High static efficiency obtainable.
(b) Economical from moderate thicknesses, about $^1/_2$ in., upward.
(c) Undesirable in severe fatigue or impact.
(d) Undesirable when bending tension can come on root of weld.
(e) One member only need be grooved.
(f) Root face facilitates assembly and prevents closing of joint during welding.

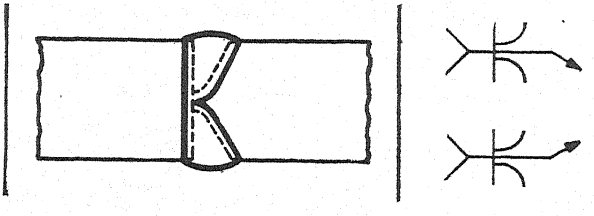
SINGLE-J, BUTT JOINT. WELDED BOTH SIDES.



Joint 19

(a) Highest static efficiencies obtainable.
(b) Economical from moderate thicknesses, about $^1/_2$ in., upward.
(c) Chipping of root easy.
(d) Root faces facilitate assembly and prevent closing of joint during welding.
(e) One member only need be grooved.
(f) If root is chipped or good penetration otherwise secured, high efficiencies can be obtained in fatigue and impact; higher if reinforcements are removed.

DOUBLE-J, BUTT JOINT

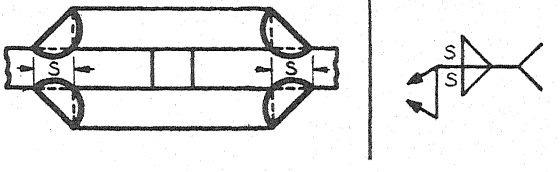


Joint 20

(a) Highest static efficiencies obtainable.

(b) Most economical in the heaviest thicknesses.
(c) May be symmetrical about center line or asymmetrical as desired.
(d) Chipping of root not as easy as Joint 17, and there is likelihood that joint may not be as good as Joint 17.
(e) One member only need be grooved.
(f) If root is chipped or good penetration otherwise secured, high efficiencies can be obtained in fatigue and impact; higher if reinforcements are removed.

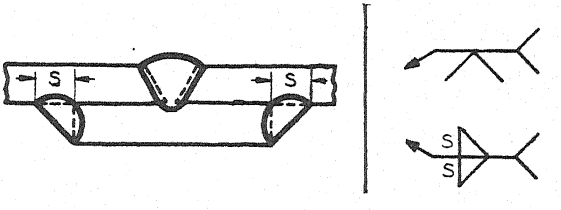
OPEN, DOUBLE-STRAPPED, BUTT JOINT.



Joint 21

(a) Joint capable of developing high static efficiency depending on size of welds used.
(b) Excess weight of straps undesirable.
(c) Fillet welds cause concentrations of stress that in fatigue and impact would be undesirable.
(d) Joint not as economical as a butt joint.

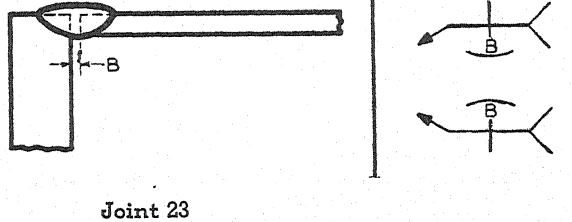
SINGLE-STRAPPED, SINGLE-V, BUTT JOINT.



Joint 22

(a) Joint capable of developing high static efficiency.
(b) Excess weight of strap undesirable.
(c) Fillet welds cause concentrations of stress that in fatigue and impact would be undesirable.
(d) Eccentricity of strap causes joint to bend under load.
(e) Butt joint alone capable of carrying load and fillet welds cause excess cost.

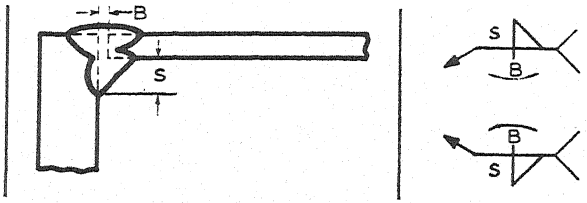
OPEN, SQUARE-GROOVE, CORNER JOINT.



Joint 23

(a) Complete penetration possible in relatively thin materials, about $^3/_{16}$ in. maximum.
(b) Relatively high efficiencies obtainable in shear.
(c) Should not be used in fatigue or impact.
(d) Should not be used when bending tension can occur in root of weld. Direct tension on either member can cause bending tension at root.

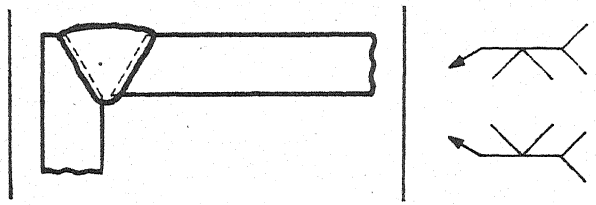
OPEN, SQUARE-GROOVE, CORNER JOINT. FILLET-WELDED.



Joint 24

(a) High efficiencies obtainable in static loading.
(b) Not particularly desirable in severe fatigue or impact.
(c) Complete penetration possible in relatively thin materials, about $^1/_4$ in. maximum.

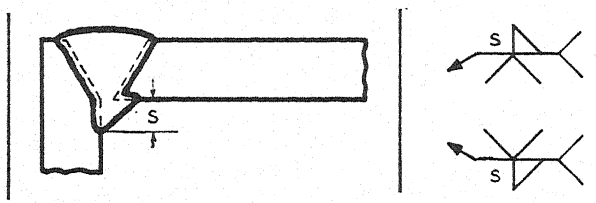
SINGLE-V, CORNER JOINT



Joint 25

(a) Relatively high efficiencies obtainable in shear.
(b) Should not be used in fatigue or impact.
(c) Should not be used when bending tension can occur in root of weld. Direct tension on either member can cause bending tension at root.
(d) Economical in moderate thicknesses, about $^5/_8$ in. maximum.

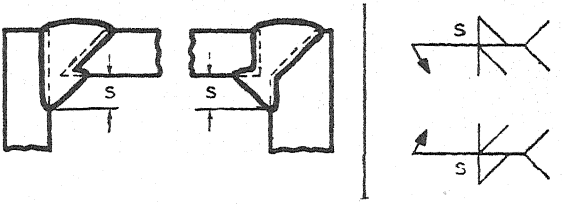
SINGLE-V, CORNER JOINT. FILLET-WELDED.



Joint 26

(a) High efficiencies obtainable.
(b) Not particularly desirable in severe fatigue or impact, due to concentration of stress at toes of fillets.
(c) Economical in moderate thicknesses, about $^5/_8$ in. maximum.

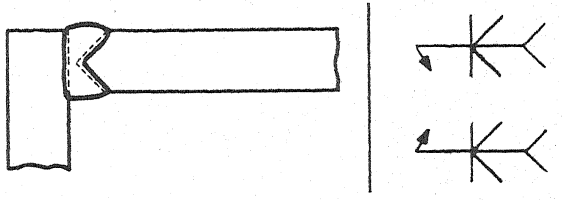
OUTSIDE, SINGLE-BEVEL CORNER JOINT. FILLET-WELDED



Joint 27

(a) High efficiencies obtainable.
(b) Not particularly desirable in severe fatigue or impact, due to concentration of stress at toes of fillets.
(c) One member only need be beveled.
(d) Economical in moderate thicknesses, about $^5/_8$ in. maximum.

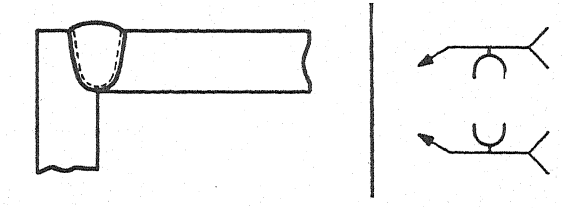
DOUBLE-BEVEL, CORNER JOINT.



Joint 28

(a) High efficiency obtainable in static shear.
(b) Economical in intermediate thicknesses of plate, about 1 in. maximum.
(c) Chipping of root very difficult.
(d) One member only need be beveled.
(e) Neither member should be subjected to severe tension because of concentrations of stress at corner.
(f) Not advisable in severe impact or fatigue.

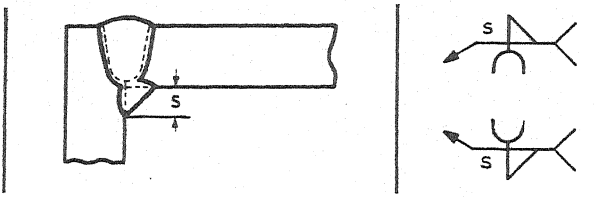
SINGLE-U, CORNER JOINT.



Joint 29

(a) High efficiencies in static shear obtainable.
(b) Economical from moderate thicknesses, about $^1/_2$ in., upward.
(c) Undesirable in fatigue or impact.
(d) Undesirable when bending tension can come on root of weld. Direct tension on either member can cause bending tension on root.

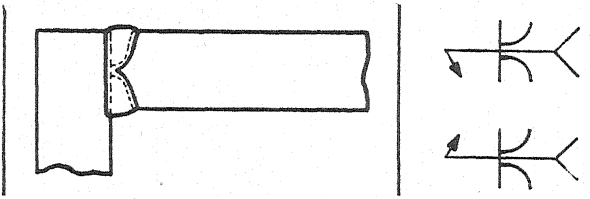
SINGLE-U, CORNER JOINT. FILLET-WELDED.



Joint 30

(a) Highest efficiencies in static shear obtainable.
(b) Economical from moderate thicknesses, about $^1/_2$ in., upward.
(c) Chipping of root easy and accessible.
(d) Root faces facilitate assembly and prevent closing of joint during welding.
(e) Not particularly desirable in severe fatigue and impact due to concentrations of stress at toes of fillet.

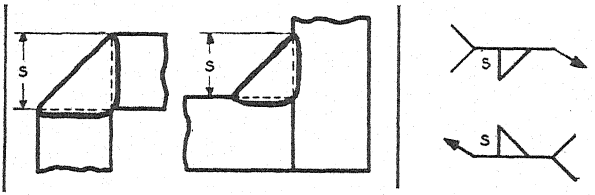
DOUBLE-J, CORNER JOINT.



Joint 31

(a) High efficiencies obtainable in static shear.
(b) Most economical in the heaviest thicknesses.
(c) Chipping of root not as easy as Joint 30, and there is likelihood that joint may not be as good as Joint 30.
(d) One member only need be grooved.
(e) Neither member should be subjected to severe tension because of concentrations of stress at corner.
(f) Not advisable in severe impact or fatigue.
(g) Root face facilitates assembly and prevents closing of joint during welding.

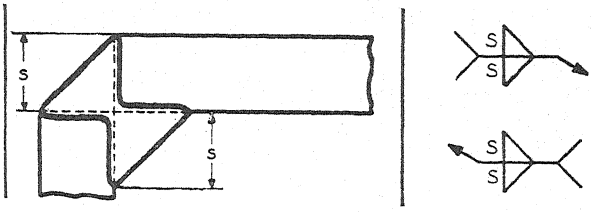
OUTSIDE-(AND INSIDE) SINGLE-FILLET-WELDED, CORNER JOINT.



Joint 32

(a) Capable of developing high efficiencies in static bending with bending tension on the face.
(b) Will fail at low values if root of weld is subjected to tension. Direct tension on either member will subject the root of the weld to tension.
(c) High efficiencies obtainable in static shear.
(d) Not economical when fillets are of large size.
(e) Should not be used in impact and fatigue.

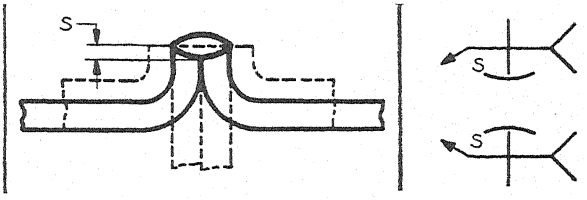
DOUBLE-FILLET-WELDED, CORNER JOINT.



Joint 33

(a) High efficiencies obtainable in static shear.
(b) Can develop good efficiency in static bending.
(c) Uneconomical in greater than moderate thicknesses of plate.
(d) Not particularly desirable in severe impact and fatigue because of concentrations of stress at toes of fillet.

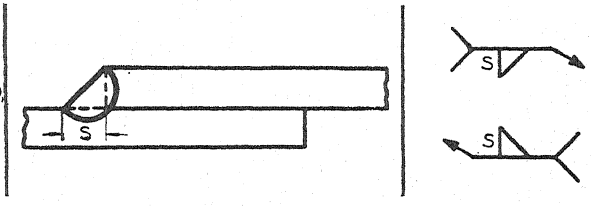
SQUARE-EDGE JOINT.



Joint 34

(a) Should not be used when either member is subjected to direct tension.
(b) Should not be used when joint is subjected to bending so that bending tension exists at root of weld.
(c) Capable of developing high efficiencies in shear.
(d) Limited penetration only can be obtained.
(e) Should not be used in impact or fatigue.
(f) Economical joint for unimportant joints in multiple production.

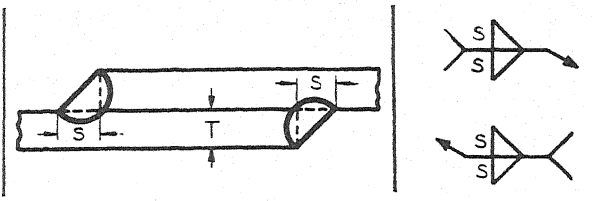
SINGLE-FILLET-WELDED LAP JOINT



Joint 35

(a) Should not be used when root of weld can be subjected to bending. Will distort out of line under tension, subjecting root to bending tension.
(b) Capable of developing high efficiencies in shear.
(c) Should not be used in impact or fatigue.
(d) Economical in moderate thickness.

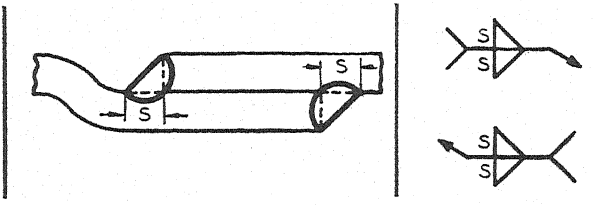
DOUBLE-FILLET-WELDED, LAP JOINT



Joint 36

(a) Can develop high efficiency in tension when lap is 5 T or more.
(b) Undesirable in fatigue or impact, due to concentrations of stress at toes of fillets.
(c) Will distort out of line functioning as an expansion joint (rotate under tension.)
(d) Capable of developing high efficiencies in shear.
(e) Easy to fit.
(f) Economical in moderate thicknesses.

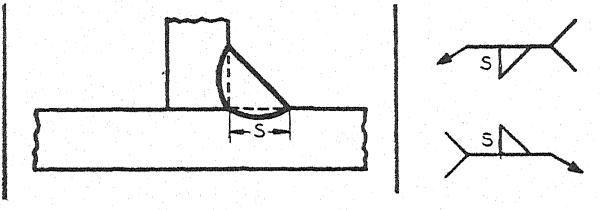
DOUBLE-FILLET-WELDED, JOGGLED, LAP JOINT



Joint 37

(a) Capable of developing high efficiencies in shear.
(b) Under static tension will distort greatly and will fail in joggle at some efficiency less than 100%.
(c) Functions as expansion joint (compression and tension).
(d) Easy to fit.
(e) Undesirable in fatigue or impact due to concentrations of stress at toes of fillets.
(f) Useful for obtaining flush surface on one side of plating.

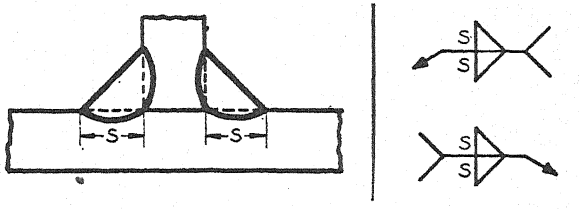
SINGLE-FILLET-WELDED, TEE JOINT



Joint 38

(a) Capable of developing high efficiencies in static bending with bending tension on face.
(b) Will fail at low values if root of weld is subjected to tension.
(c) Will fail at low value if perpendicular member is subjected to direct tension.
(d) Capable of developing high strength in shear.
(e) Should not be used in fatigue or impact.

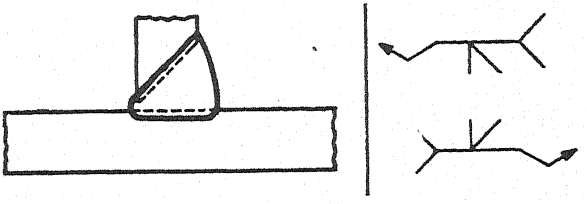
DOUBLE-FILLET-WELDED, TEE JOINT.



Joint 39

(a) Capable of developing high efficiencies in static tension, compression, shear and bending.
(b) Inadvisable to use in severe fatigue or impact, because of concentrations of stress at roots of fillets.
(c) Uneconomical in greater than moderate thicknesses.

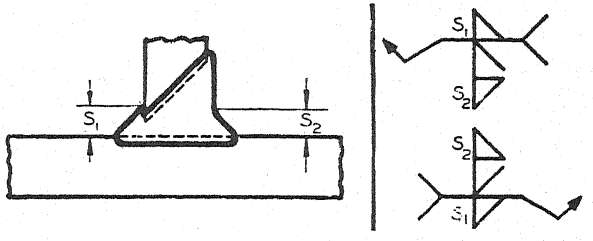
SINGLE-BEVEL, TEE JOINT.



Joint 40

(a) Relatively high static efficiencies obtainable in shear.
(b) Undesirable to use in fatigue or impact due to concentrations at corners.
(c) Should not be used when bending tension can occur in root of weld.
(d) Economical in intermediate thicknesses, about $^5/_8$ in. maximum.
(e) One member only need be beveled.

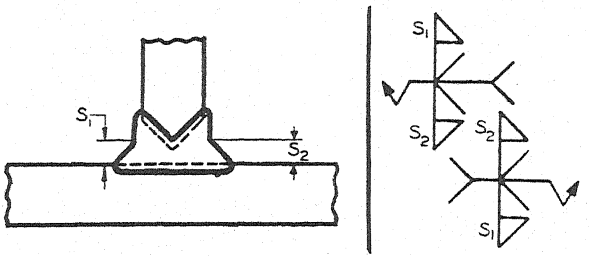
DOUBLE-FILLET-WELDED, SINGLE-BEVEL, TEE JOINT.



Joint 41

(a) Highest efficiency can be developed in static tension, compression, shear and bending.
(b) Economical in intermediate thicknesses, about $^5/_8$ in. maximum.
(c) One member only need be beveled.
(d) Root accessible for chipping.
(e) Moderately good efficiency in fatigue and impact can be obtained.

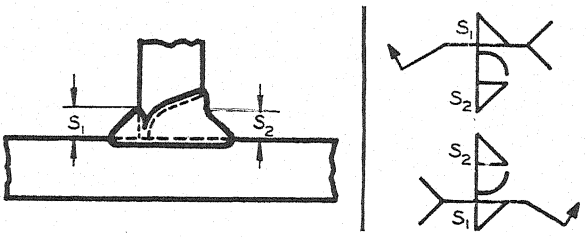
DOUBLE-FILLET-WELDED DOUBLE-BEVEL, TEE JOINT.



Joint 42

(a) Highest efficiency can be developed in static tension, shear, compression and bending.
(b) Economical in moderate thicknesses, about 1 in. maximum.
(c) One member only need be beveled.
(d) Chipping of root somewhat more difficult than Joint 41.
(e) Moderately good efficiency in fatigue and impact can be obtained.

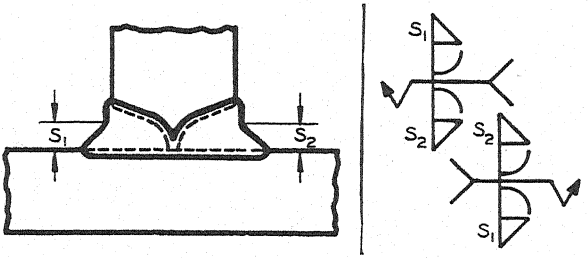
DOUBLE-FILLET-WELDED, SINGLE-J, TEE JOINT.



Joint 43

(a) Highest efficiency can be developed in static tension, compression, bending and shear.
(b) Economical in intermediate to heavy thicknesses.
(c) Root accessible for easy chipping.
(d) Root face facilitates assembly and prevents closing of joint during welding.
(e) Moderately good efficiency in fatigue and impact can be obtained.

DOUBLE-FILLET-WELDED, DOUBLE-J, TEE JOINT.



Joint 44

(a) Highest efficiency obtainable in static tension, compression, bending and shear.
(b) Economical in the heaviest thicknesses.
(c) Chipping of root not as easy as Joint 43.
(d) Root face facilitates assembly and prevents closing of joint during welding.
(e) Moderately good efficiency in fatigue and impact can be obtained.

CHAPTER 32B

THERMAL STRESSES AND THEIR RELIEF*

General Consideration of Residual Stresses, Effect of Residual Stresses in Service, Physical Properties Affecting Residual Stress, Rigidity of Structure, Planning for Structural Freedom or Flexibility, Methods of Stress-Relief, Shrinkage Distortion in Welding.

FOREWORD†

THE satisfactory behavior of welded structures in service is predicated upon sound welds. The obtaining of sound and properly fused welds, free of checks and incipient cracks, as well as slag, porosity, blow-holes, and the like, is therefore of major importance. To this end procedure includes much more than sequence of welding; in fact, other factors such as preheat, the continuity of the welding operation, peening, and an endeavor to assure a uniform distribution of stress over the joint are often of equal importance.

Procedure also shares importance with other factors in this matter of obtaining sound welds, namely, adequate inspection, suitable equipment, the proper training and qualification of operators and, not least important, the accessibility of the joint. Even the most carefully developed procedure cannot be depended upon to compensate for deficiencies in the other requisites for sound welds.

Residual stresses compose an internal force system which obviously must be in equilibrium. When such a system is subjected to externally applied loads, there is no simple addition to like forces from which to conclude that some local point may be overstressed. For example, externally applied loading in tension cannot be additive to residual stresses of like sign until the balancing compressive stresses of the system in equilibrium are overcome. This principle is well established as in the case of pre-loaded bolts in cylinder head joints and has been demonstrated in a variety of test devices.

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† This foreword is abstracted from a report on Thermal Stresses prepared by the Committee on Marine Construction, A. W. S.

* Material for this Chapter originally prepared for 1938 Edition by S. C. Hollister, Cornell University. Revised by a committee consisting of W. Spraragen, Welding Research Committee, *Chairman;* La-Motte Grover, Air Reduction Sales Co.; C. H. Jennings, Westinghouse Elec. & Mfg. Co.; H. E. Rockefeller, The Linde Air Products Co.; D. S. Jacobus, *Honorary Chairman,* A. S. M. E. Boiler Code Committee.

A rolled shape, as delivered from the steel mill, is in a similar state of locked-up stress. Investigators have measured residual stresses up to the yield point existing in rolled sections.[1] An indication of these stresses is the warpage of an I-beam when the web is split to form two T-sections, yet these beams are used safely under the assumptions of our beam formulas.

A further consideration which reduces the importance of residual stresses is the property of mild steels, all of relatively high ductility, to elongate under stress. Although the yield point is reached in comparatively slight extension, considerable elongation is required before such steels reach the point of failure. Before local points reach any appreciable part of this elongation the load has been re-distributed with adjacent material assuming a larger proportion. This principle has been used for years in the "stretcher-leveling" of steel plates. In this method, the tendency of a plate to buckle and warp after rolling due to residual rolling stresses is removed by stretching the plate beyond its original elastic limit, thus re-distributing the stresses in a more uniform manner.

There is considerable evidence that residual stresses, whether induced by cold work such as rolling, bending, or flanging, or by hot work, either welding or shrinking, tend to distribute themselves and to reduce peak values particularly when subjected to external loading. Stress-relieving by furnace treatment is in part an accelerated seasoning process. The critical time, therefore, in a welded structure is a period of somewhat indeterminate length beginning immediately after the welded joint is made. If exposed to sudden changes of temperature which induce highly localized stress before reasonable seasoning can take place, there is the possibility of failure. There have been few such cases in ship building; nevertheless, they are not unknown and appear to account for the majority of plate or joint failures particularly during the winter months in northern yards.

It is impracticable to set a limit on thickness of low carbon steel plating in which the presence of residual stresses is of minor importance. Experience in welded ships indicates that plates up to 1 in. thick may be welded successfully although restrained from free shrinkage. The rigidity of a structure, however, depends not only upon the thickness of plating, but on the relative degree of stiffening, the size and relative dimensions of unsupported panels, and many other factors which make generalization impossible.

General Consideration of Residual Stresses

Metal deposited by either the gas or electric arc processes is in a highly superheated molten state as are also the surfaces to be joined. As the deposited metal and surface cool they shrink. The shrinkage is volumetric or three dimensional; that is, the weld metal contracts on cooling in thickness, width and length and, in doing so, draws on the base metal to which it is fused. This drawing action leaves stresses when cooling is concluded.

[1] MATHER, JOSEF, "Determination of Initial Stresses," *A. S. M. E. Transactions*, 1934; also A. W. S. JOURNAL, July 1934.

Due to the resistance of the base metal adjacent to the weld, the stress parallel to the joint is usually the greatest. The stresses in the other two directions are dependent on the width of the weld, the thickness of the plate and the degree of restraint. Such stresses are called *residual stresses due to welding*. Any process subsequently applied which results in a material reduction or complete removal of such stresses is called *stress-relieving*.

Residual stresses are introduced in part by the partial heating of the metal adjacent to the weld, followed by irregular cooling. If the surrounding parts offer considerable resistance to distortion, the residual stresses are increased due to such restraint. One of the chief factors affecting the magnitude of the residual stresses is the degree of rigidity of the structure. The rate and sequence of welding are other important factors.

Even a short length of weld generally causes plastic yielding so it may reasonably be assumed that localized stresses equal to the yield point exist in any joint in the "as welded" condition.

The problem is whether these stresses are serious, and if so, for what types of service. Their effect on service load conditions, therefore, is of great practical importance. Whether such effects are serious depends upon the state of combined stress when stresses due to load are added to those existing residually before the load is applied. Each form of member or structure, with its inherent residual stress, combined with each different service condition, presents a problem to be judged on its own merits; and no simple general rule can be applied because of the large number of possible combinations. Certain broad principles may be formulated, however, to serve to guide judgment as to the seriousness of residual stress in a given member, and hence as to the need for stress-relieving.

There is a corollary problem involved in the matter of distortions. Any structure having high residual stresses approaching the yield point of the material will tend to plastically yield slightly with any additional load if not too rapidly applied or if the structure is not so rigid in a three-dimensional manner as to prevent such yielding. Thus any slight yielding will automatically relieve some of the stress but some permanent distortion will take place. In many cases these distortions in service are insignificant. In others they are of the utmost importance and a few hundredths of an inch may destroy the utility of the structure as, for example, bearings for rotating elements.

Consider two long plates butt-welded as shown in Fig. 1 (*a*). The weld metal contracts, and in so doing shortens somewhat the length of the weld. The plates offer resistance to free contraction of the weld lengthwise; thus the weld is finally in longitudinal tension, and the plate is in compression, as shown in Fig. 1 (*b*). The areas C (compression) must equal T (tension) otherwise equilibrium would not exist on section *a-b*. Should the weld be split along *c-d*, the weld shortening would cause edgewise curling of the plate as in Fig. 1 (*d*) where the amount of curling is greatly exaggerated; hence the stresses crosswise of the weld, before splitting, would be as shown in Fig. 1 (*c*). Here again, the areas C (compression) must equal the area T (tension) for equilibrium on *c-d*.

Suppose now a uniformly distributed endwise tension be applied on the plate, within the elastic range (see Fig. 2). The residual stress (*a*) would be added algebraically to the uniformly distributed load stress (*b*) to result in the final stress state (*c*). If the load stress is increased gradually, the central zone along the weld would reach the yield-point stress, resulting in a larger proportion of the stress being carried by the side zones, as in (*d*). Finally, of course, the entire width of plate would reach yield-point value, and the stress would then be distributed uniformly, as in (*e*) assuming of course, the material was sufficiently ductile.

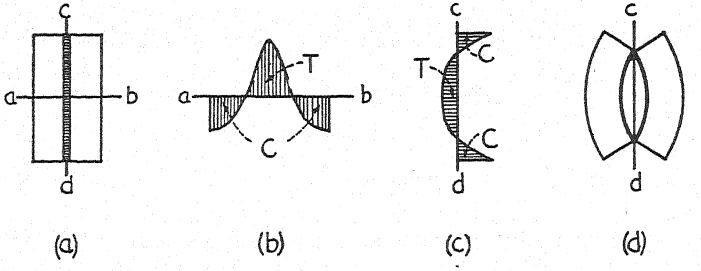


Fig. 1

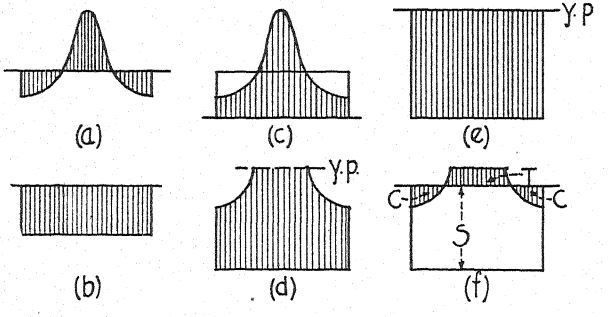


Fig. 2

If the load were then removed, the plate would return elastically to a state of no stress, because the contracted weld metal (and narrow zone adjacent to it) had been stretched plastically an amount such that its free length is the same as that of the unwelded plate.

If the load had been released following the state shown in Fig. 2 (*d*), elastic return would have resulted by subtracting the load stress *S* in

(*f*), and the residual stress would have been such that area *T* equaled the combined areas *C*, for equilibrium on the cross-section.

Here again, the application of *gradually* applied load resulted in stress-relief. Other methods which would have resulted in plastically deforming the portions under high residual stress would have accomplished similar results.

Will Residual Stress Disappear with Time?—Many assertions have been made that residual stresses will in time disappear, and that they may therefore be disregarded. There is too much well-founded evidence to the contrary to permit acceptance of such statements, so far as the steels are concerned. Residual stresses are found in locomotive drivers due to shrinking on tires; or in car wheels, due to forcing them on the axles. They are found in riveted and bolted connections, and in boilers in which tubes are rolled into the tube sheets. In all these cases, and in numerous others, the integrity of the connections depends upon the continuance of the residual stresses; and experience has justified reliance in such joints. Only in the event that *plastic deformations are developed*, through additional loads, heating, peening or otherwise—even though such processes are applied slowly over a long period of time—may residual stresses be expected to be reduced.

Where plastic yielding is possible in relatively thin material (one inch or less) the endurance limit of parts having high residual stresses is not much lower than that of similar parts which have been stress-relieved. This is not the case in drums and shells of thicker material where standard construction codes require stress-relief in order to secure safe results. There are, of course, many structures which can be safely welded without stress-relief. In these the shrinkage stresses become less in service, because of the plastic deformation at points of high residual stresses. In such structures the procedure in welding any heavy seams should be such as to keep the residual stresses as low as practicable.

Importance of Residual Stresses in Service

In the cases considered above, the increase in load stress to such values that yield-point stresses developed at regions of high residual tensile stress resulted in reduction of residual stresses. In a majority of members of mild steel subject to very gradually applied load stresses, or to steady stresses, residual stresses are not of serious importance. In cases where the loads are suddenly applied, however, plastic deformations may not have time in which to develop, with the result that the high tensile residual stresses may become serious. In such cases stress-relief either by heat treatment or by static preloading is highly desirable.

If the structure is rigid (three dimensional) and the loading involves repeating or reversing stresses, the stress range at a given point is that resulting from the algebraic addition of the range of load stress to the residual stress; and the result may become very serious. It is highly important that such fatigue conditions be carefully controlled by suitable stress-relieving.

Creep, which is a slow plastic deformation occurring in steel only at elevated temperatures, usually reduces residual stresses in time, if they

are large enough to enhance such plastic readjustment. Where undesirable distortion may result from the release of residual stress due to the high temperature, the presence of such stress may be of great importance.

Low temperatures affect many metals by reducing their resistance to shock. In such cases residual stresses should be reduced or eliminated by adequate stress-relieving.

Members which are to be machined after welding, as, for example, machine parts, and which have not been stress-relieved, may possibly distort during the machining operation, dependent upon the amount and distribution of the residual stresses and the extent of the cutting. In such cases it is sometimes necessary to stress-relieve before machining.

In vessels subjected to corrosion the rate of corrosion is increased at the points where there are localized stresses. When supporting lugs are fusion welded to a vessel and the entire vessel is not stress relieved afterward, the increased corrosion on the inside of the vessel opposite the welds will sometimes give a clear outline of the form of the lugs.

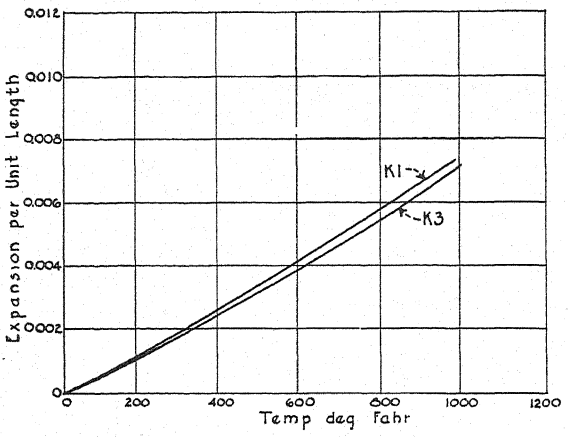


Fig. 3

Table 1—Chemical Compositions and Other Details of the Two Steels of Figs. 3 and 5

Mark	Chemical Composition, Per Cent							Rolled to	Preliminary Heat Treatment	Heat Treated by Lab. No.
	C	Mn	P	S	Si	Cr	Mo			
K1*	0.17	0.42	0.012	0.035	..	..	..	1 in. round	1650–1700°F. (900–925°C.), 1 hr. cooled in air	23
K3*	0.39	0.51	0.005	0.029	0.19	0.87	0.21	1⅛ in. round	1625°F. (885°C.), 2 hr. cooled in air 1550°F. (845°C.), 1½ hr. cooled in oil 1300°F. (705°C.), 2 hr. cooled in oil	13

* Analysis made by manufacturer of the steel.

Physical Properties Affecting Residual Stress

The initial factor among the physical properties which create residual stress is thermal expansion. Table 1 gives the chemical compositions and details of a mild and an alloy steel and Fig. 3 gives the expansions in a unit of length. The alloy steel has somewhat less expansion than the mild steel. (See *A.S.T.M. Proc.*, **27** (I), 145–157.)

A rise of 100°F. gives an elongation of about 0.00065 in. per in., or an increase comparable with that under a tension of 20,000 psi. A temperature differential of 100°F. in an element anchored at each end results in a stress of the magnitude indicated above.

Lea and Crowther give the effect of rise in temperature on the modulus of elasticity of mild steel as shown in Fig. 4. The modulus at 1200°F. is only a third of that at room temperature, while from room temperature to 600°F. there is only a small reduction. (See *Engineering*, **98**, 488.)

Fig. 5 shows the great reduction in tensile strength and yield point, and large increase in elongation, due to temperature increase, for the steels of Table 1. Thermal stress-relieving of mild steel (K1) at 1150°F. greatly reduces the stress at which plastic yield may take place. On the other hand, a cooling weld is developing greater yield strength (also stiffness, from increasing modulus) as the temperature decreases.

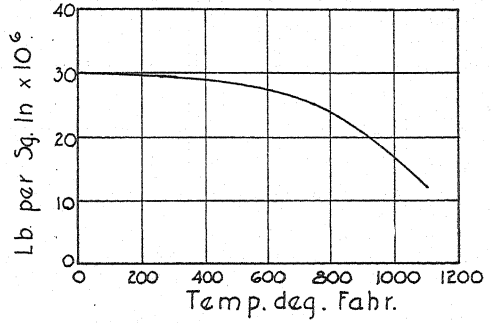


Fig. 4

It is clear from Figs. 4 and 5 that the cooling of mild steel welds from the molten state down to 600°F. is accompanied by considerable yielding; but that below this temperature, due to a nearly constant yield point and modulus, the residual stresses will develop rapidly depending on restraint to free movement offered by the member or structure.

Figure 6 shows the stress-strain diagrams for structural steel (*A*) and hard steel (*B*). Of major importance in members having residual stresses is the presence of a well-defined yield range well below the ultimate strength at *a* in the former, and the yield range near the ultimate in the latter. In addition, the difference in plastic elongation before rupture is considerable. Because of these differences, mild or other steel having a well-defined yield point will tend to relieve itself by plastic yielding when the yield range is reached, whereas the steel of the type *B* will not tend to relieve itself readily until near ultimate load.

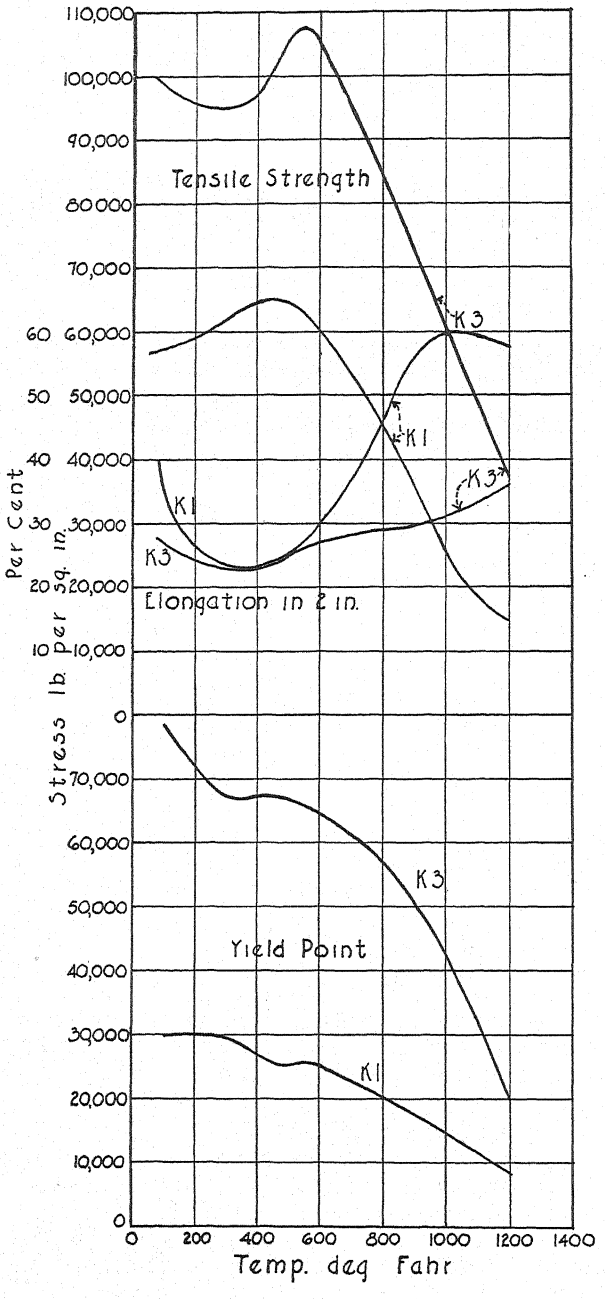

110,000
100,000
90,000
80000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Tensile Strength
K3
K1
K3
K1
K3
Elongation in 2 in.
Per Cent
Stress lb. per sq. in.
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
K3
Yield Point
K1
0
200
400
600
800
1000
1200
1400
Temp. deg Fahr

Fig. 5

Rigidity of Structure

The most important characteristic of a given structure to influence the amount of residual stress likely to result from welding is its rigidity. Rigidity may be one-, two- or three-dimensional. As an example of one-dimensional rigidity consider a narrow flat bar having a butt-weld joint at its center. If the two pieces were free to move while being welded there would be no rigid restraint, considering the member as a whole. If, on the other hand, the outer ends of the two pieces were firmly fixed so they could not move, the forming of the butt weld would produce a tensile stress throughout the length of the piece. The tensile stress is caused by the shrinkage of the butt weld. It is easy to see that the tension set up in a long, fixed bar is less than it would be if the bar were short.

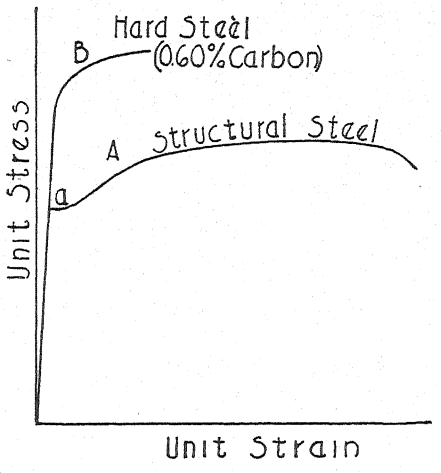


Fig. 6

Suppose now instead of a narrow bar, a butt-weld joint had been made in a wide plate, the outer ends of which were anchored as before. In this case there is a tension produced in the plate from anchor to anchor, which tension is greater the shorter the distance between anchors. In addition to this tension, the plate is tending to contract laterally due to the endwise shrinkage of the weld. This lateral contraction of the plate could take place more freely if the plate's dimension between anchors was very long in proportion to its width. If the distance between anchors is short, however, then the anchors themselves prevent free lateral contraction of the plate, with the result that a considerable tension is caused across the plate at the weld. This case is a very common example of two-dimensional rigidity.

Suppose now the wide plate is anchored not only at its ends but also at its sides. Here again, two-dimensional rigidity is to be found, these two dimensions involving length and width.

It may be noted that in the first case of the narrow flat bar there is only

small amount of restraint in the vicinity of the weld itself in the transverse direction. The wider the bar the more important the stress from this source becomes. For very long members this stress practically disappears at distances from the weld equal to the width of the piece.

A very common example of two-dimensional rigidity is to be found in the simple case of butt-welding two wide plates that are not anchored in any way and are thus free to move. In this case the rigidity results from the resistance of these plates to distortion while being welded. The nature of the stress distributions in the two directions has already been noted in Fig. 1.

It may now be seen that the degree of restraint arises from either of two sources: (*a*) anchorage of the sides or ends of the members being welded; and (*b*) resistance of the parts themselves to distortion during welding. In general, it may be said that the second of these restraints is always present in some amount, depending upon the dimensions of the piece and the dimensions of the weld. If the stresses thus produced are not large, stress-relieving may not be necessary. On the other hand if the stresses are large, stress-relief may be necessary. Some structures are capable of developing resistance during welding in three dimensions—that is, in the directions of length, width and height.

Butt-welded plates usually are problems in two-dimensional rigidity. A common example is shown in Fig. 7, in which a circular plate is to be

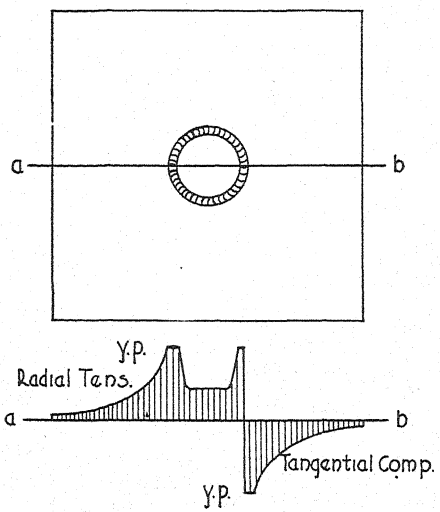


Fig. 7

butt-welded into a circular hole of slightly larger diameter. The large plate having a hole, however, is under quite a different state of stress; as the weld metal contracts the hole is drawn to a smaller diameter. There is thus a tension in the plate in the direction of the radius of the hole; and a compression in the direction of a circular path concentric with the hole is set up to resist the reduction in the size of the hole.

An example of three-dimensional rigidity is to be found in a plug weld (see Fig. 8). In this case the plug weld is virtually a fillet weld formed around the periphery of the hole. The restraint is formed by the following resistances:

(*a*) The plate resists contraction of the diameter of the hole, thus producing tension in a radial direction.

(*b*) Due also to the same resistance of plate against reduction in the size of the hole a compression is produced in the direction of the periphery of the hole.

(*c*) The two plates are in contact with each other and hence they resist the pull of the cooling weld metal in the direction of the thickness of the plates.

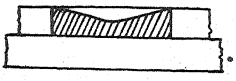


Fig. 8

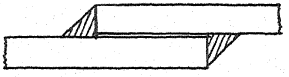


Fig. 9

Planning for Structural Freedom or Flexibility

Members having great rigidity sometimes crack in or near the weld either during or immediately after welding. This is especially true if the member is being made of metal having a yield range near the ultimate strength. It is thus important to adapt a welding sequence or other features of procedure to the particular kind of restraint, whether the member is ultimately stress-relieved or not.

Figure 9 shows two sections of pipe being attached by fillet welds. If the pipes are not anchored at their outer ends, resistance in the direction of the length of the pipe does not exist. If the two pipes are in close contact the fillets meet with great resistance in the direction of the radius of the pipe. This may frequently be greatly relieved by not having the pipes in contact; in which case the outer pipe may move inward and the inner pipe move outward. In like manner the contraction of the weld in the hoop direction may be relieved considerably by not having the two pipes in contact.

Frequently one part of the structure being joined may be preheated to good advantage; so that as this part cools it will move in the direction of the drawing tendency caused by the cooling of the metal. Preheating has the further advantage of reducing the sharpness of the temperature gradient in the parent metal adjacent to the weld.

Intermittent welding is frequently found advantageous because it distributes rather than accumulates the draw of the weld. Sometimes also, it is desirable to make a continuous weld by making two or more intermittent passes, the subsequent ones closing the gaps between the intermittent welds of the first pass.

Methods of Stress-Relief

The most common method of stress-relief is by heat treatment. It has been noted in Fig. 5 that the yield point decreases with increase in temperature so that for mild steel the yield-point stress at 1200°F. has been reduced to 8000 psi. or less. Any stresses above this amount produce a

flow in the steel and are thus relieved. To accomplish this result it is necessary that the member be heated uniformly and that it be held a sufficient length of time for the relieving plastic flow to take place. Since plastic flow or creep will begin at the elastic limit, which is below the yield point, the final residual stress will be below 8000 psi., dependent also upon the period of maximum heat, and upon the degree of restraint.

Any furnace capable of uniform heating, under temperature control, is satisfactory for the treatment. The method of heating must, of course, be one not injurious to the metal being treated. Care must be exercised in providing support to prevent distortion of the members. The rise in temperature must be gradual and the rate such that all parts are being heated throughout their thickness at a uniform rate. The maximum temperature commonly employed for mild steel (structural or boiler plate) ranges from 1100 to 1200°F. Other steels may require a higher temperature, dependent upon the reduction in yield point, and the yield characteristics of the material. For some alloys it is necessary to advance the soaking temperature to 1600°F. or above.

The length of time the member should be held at the maximum or soaking temperature depends upon the thickness of the parts, and the plasticizing rate of the steel of which it is made. For pressure vessels and other structures of mild steel, having uniform thickness or uniform degree of restraint, the soaking period is commonly one hour per inch of thickness of material. Structures having parts of widely different thickness should be held longer at the soaking temperature to insure relief in and about the thickest parts. Adequate support of lighter parts must be provided; otherwise serious distortion of them may result.

The reduction of the temperature must be gradual, and at a rate which will insure approximately uniform temperature throughout all parts. Structures of widely variable thickness or restraint may require as much as 48 hr., in special cases, for this operation. Simple pressure vessels of uniform thickness may properly be brought down much more rapidly, consistent with near uniformity of temperature throughout the thickness of material.

The temperature at which the member may be withdrawn from the chamber depends upon a number of conditions. It must be remembered that a temperature differential of 100°F. in a rigidly fixed piece is equivalent to 20,000 psi., at temperatures below 600°F. It is therefore especially important that members having within themselves variable rigidity or restraint be reduced uniformly to the atmospheric or ambient temperature; otherwise new residual stresses will result. It is exceedingly important that even simple vessels, such as drums of uniform thickness, be cooled uniformly if new stresses are to be avoided. Thus a still air is very desirable after the furnace is opened and until the piece is fully cooled. The care with which this final stage of cooling is controlled may be regarded as exceedingly important for members or structures involving very heavy plates, widely varying thicknesses of parts or members of great rigidity.

Pressure vessels of simple form and uniform thickness are frequently withdrawn at 600°F., or at that temperature the furnace is opened to permit more rapid cooling. This may safely be done if the air surrounding the vessel is sufficiently quiet to insure uniform temperature. More

complex assemblies are brought to a lower temperature (in extreme cases to 200°F.) before opening the furnace.

The foregoing describes total heating of the member for stress-relief. Frequently, total heating is not possible because of the size of members, as for instance, pipe lines. In such cases it may be possible to stress-relieve by heating only a portion of the structure at a time; but this should be done with great care, so as to avoid an undue amount of restraint.

The girth joints of pipes are frequently locally stress-relieved. A strip around the pipe extending to each side of the weld a sufficient distance to cover the portion of shell originally affected by the welding is heated by a ring of burners or other heating elements, arranged within a housing to hold the heat.

The band should be heated uniformly, and the cycle and temperature range controlled as for total heating, as described above. The heating elements, together with local enclosures or blankets, should be so arranged as to provide a reasonably smooth, flat gradient along the pipe either way from the heated zone. This prevents undue distortion and restressing due to the heating operation.

Local stress-relieving by local heating should not be undertaken unless the affected part may expand and contract with comparative freedom, otherwise restressing may occur to an extent perhaps equivalent to the original residual stress.

There are several other ways of accomplishing stress-relief. In Europe it is not uncommon to apply internal pressure to pressure vessels of mild steel and to increase the pressure until the shell has reached yield-point stress circumferentially. On the removal of such pressure the circumferential residual stresses have largely disappeared in vessels with shells of uniform thickness. When there is a heavily reinforced opening in the shell there may be localized stresses around the reenforcement after releasing the pressure. Wherever this procedure is used it is important that the test be hydraulic rather than with air because in the event of rupture the use of air is very dangerous. It is important also that only a very small yielding take place in the structure, otherwise there is a danger of strain hardening or embrittling the steel.

Another method that has been employed with success is to peen the plate after welding is finished in the region in which the stresses are high. Such peening causes plastic flow and hence the relief of the restraint which causes the residual stress. Only a small amount of actual flow is necessary to accomplish the desired results. Over-peening cold-works, and therefore strain-hardens, the material; and such a result would be highly undesirable. Furthermore, overpeening may result in cracks, defects or in introducing new residual stresses, thus defeating the intended objective. Peening is difficult to control, but when properly done is an effective method. Hand peening does not have proper control and therefore would not generally be satisfactory.

Another method of mechanical stress relief is the slow (virtually static) preloading of a structure before it is placed in service.

In certain cases it is desirable to preheat the parts to be welded so that upon cooling the stresses that would otherwise accumulate due to welding will be relieved. Over- or under-heating will produce other locked-up

stresses, and it is therefore important that preheating be carefully planned and controlled.

APPENDIX

Shrinkage Distortion in Welding

There are two major aspects of shrinkage in all types of welding, namely, shrinkage distortion and shrinkage stresses. By shrinkage distortion is usually meant the over-all motion of parts being welded from the position occupied before welding to that occupied after welding. For example, the distortion of a weld made between two parts held everywhere with absolute rigidity during welding is probably zero, yet the shrinkage stresses in such a welded part may be high. On the other hand, the distortion of a completely stress-relieved, or highly preheated weld between two parts free to move during welding may be large, whereas the residual shrinkage stresses may be small.

Butt Welds—

The following factors affect the shrinkage perpendicular to the weld:

1. Cross-sectional area of weld for a given thickness of plate—the larger the cross-section the greater the shrinkage;
2. The angle of scarf is not nearly as important as "free-distance" or spacing between roots in causing distortion perpendicular to the weld;
3. Total heat input. The greater the total heat input, the greater the amount of distortion;
4. Rate of heating; Other factors being equal, greater rate of heat input results in less distortion; applies also to angular distortion;
5. Wandering (skip) and step-back procedures of welding lessen the amount of distortion;
6. Peening properly used is effective in reducing the amount of distortion but is not recommended unless very careful control and supervision are furnished.

The following factors affect angular distortion:

1. Angular distortion of V joints free to move increases with the number of layers.

2. Angular distortion is greatest in V welds, next in U and least in double-V and double-U welds.

3. Angular distortion may be practically eliminated in double-V or double-U welds by welding alternately on both sides in multilayer welding.

4. Angular distortion may be controlled by peening of every layer to a suitable extent.

5. Time of welding and size of electrode have an important bearing—(rate of total heat input).

Fillet Welds—Shrinkage

In making fillet welds it will be found that shrinkage:

(1) increases with size of weld and decreases as the rate of heat input increases;

(2) if weld is intermittent, is proportional to the length of the weld;

(3) may be decreased materially by suitably choosing sequence and procedure of welding and peening;

(4) transverse shrinkage is less for a lap joint than for a V-butt weld.

Angular distortion is reduced by preheating, and by suitably arranging the sequence of welding, e.g., staggering.

CHAPTER 32C

JIGS AND FIXTURES FOR ARC AND GAS WELDING*

Definitions, Temperature Considerations, Jigs of Various Forms, Reasons for Use of Jigs, Spacing, Miscellaneous Devices, Design Fundamentals, Locating Points, Types of Clamping Devices, Controlling Expansion and Contraction, Welding Jigs for Corrosion-Resistant Metal, Jigs for Sheet Aluminum Alloys, Heat Expansion.

Definitions

THE terms "jig" and "fixture," when applied to equipment designed to facilitate production of parts by welding, have somewhat different meanings than when applied to machine tool operations.

A jig for use on metal working machine tools is, as a rule, a device that contains guides for the respective tools to be used. Thus, a drill jig is designed to hold a part while being drilled and has hardened steel bushings for guiding the drills, reamers, counterbores and facing tools so that the pieces produced will have all holes and bosses drilled, bored and faced exactly the same.

A fixture designed for the production of metal parts on machine tools is, as a rule, something that is held or fixed on the machine on which the operation is performed, and that has no bushings or guides for the cutting tools. The cutting tools, which may be milling cutters or cutters of the planer tool type, operate on the work piece while held in the fixture and are dependent on the machine itself for guidance during the machining operation rather than on the fixture.

Obviously, these distinctions do not apply strictly to work-holding devices for welding. The function of a welding jig is of a different nature. A welding jig for the purpose of this discussion may be defined as a device which holds in established relationship parts to be welded into an assembly and which may provide for partial or complete control of the residual heat effects of welding. (Refer to Fig. 1.)

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* Based on Report of Oxy-Acetylene Committee of International Acetylene Association. Amplified by A. N. Kugler, Air Reduction Sales Company, M. S. Evans, American Car & Foundry Co., and H. E. Davies, Pollak Mfg. Co., to cover methods for arc and gas welding.

A welding fixture might be defined as a device that holds the work piece in a correct welding position convenient to the operator and which permits changing the position of the work piece at will during the process of welding in order to present the welding zone continuously in a level or otherwise convenient position. Such devices are now commercially available in the popular weld positioners (see Figs. 2, 3, 4 and 5).

A combination jig and fixture might be defined as a device that combines the functions of a jig and fixture in one, but the distinctions are vague

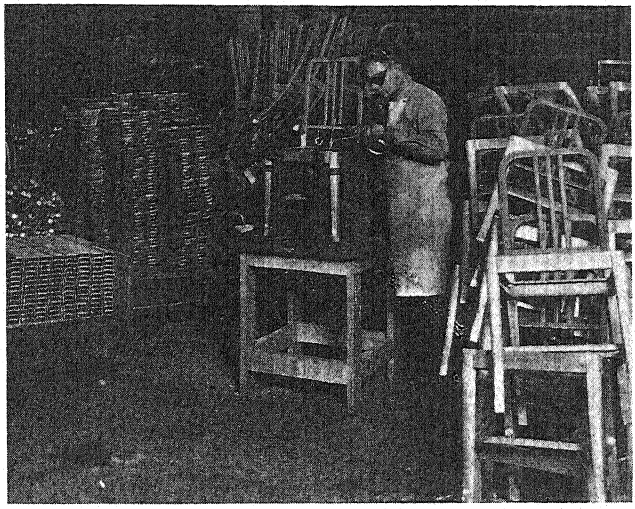


Fig. 1—A Typical Production Welding Jig for the Assembly and Fabrication of Aluminum Chairs. The Parts to Be Joined Are Carefully Located in the Required Position. The Jig Is So Designed That It Does Not Permit Any Piece to Be Assembled Out of Place

and difficult to see in all cases. Therefore, for the purpose of this chapter, work-holding devices for facilitating welding will be designated simply as welding jigs.

Temperature Considerations

Need for jigs in welding is more acutely felt when working on thin sheet metal parts ranging from, say, 10 gage ($^{9}/_{64}$-in. thickness) down through the thinner sections, than on the heavier plate metals. As a general rule, the thinner the sheet metal, the greater the need of welding jigs. The reason seems to be the relatively greater heat effect which tends to distort the metal more as the cross-section is reduced. When the welding heat is applied to comparatively heavy metal sections, expansion takes place along the three dimensions as the heat is absorbed, with little apparent distortion, warping or displacement in any one dimension. Hence, the thicker the section, the less the warping effect of the welding heat locally applied.

When heat is applied locally to a thin section, say, $^1/_{16}$ in. or less, the apparent expansion effect is magnified, because the thickness lever arm is very short and any difference in temperature between the outer metal layers under the arc or torch flame and the metal on the opposite side produces warping movements that are multiplied in inverse ratio to the thickness. That is, the less the thickness, the greater the heat distortion likely to be produced by welding. Added to this are the effects created when the welding heat releases the stresses set up by the rolling operations.

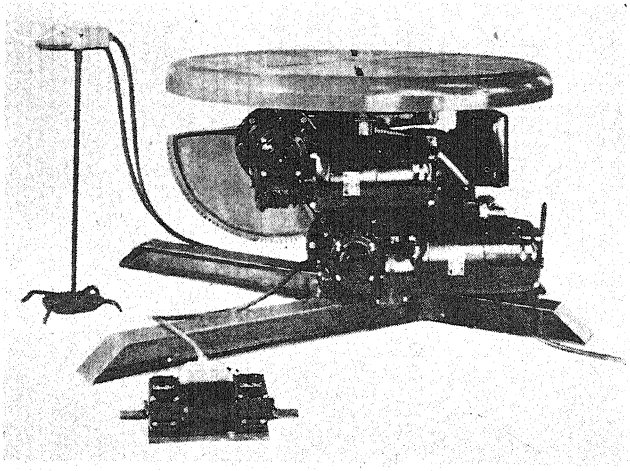


Fig. 2—A Motor-Driven Weld Positioner Which Permits of Rotation in Two Planes at 90° to Each Other

For purposes of simple illustration, a heat differential of, say, 500°F., in the upper and lower surface layers of a $^1/_{16}$-in. sheet, may be said to have approximately twice the warping effect of the same heat differential in a $^1/_8$-in. sheet. Also, the $^1/_8$-in. sheet, acting as a beam in all directions in its plane, has four times as much resistance to bending or warping as the $^1/_{16}$-in. sheet. A $^1/_2$-in. plate, by the same token, would tend to warp only one-eighth as much, and its resistance to bending would be sixty-four times as great.

Changes in the edge contours of sheets matched up for butt welding are greater relatively with thin sheet metal than with heavier or plate metal. Hence there is the need of a means for controlling warping and edge movements by absorbing heat, equalizing the effects, or forcibly restraining them in some degree.

Jigs of Various Forms

Production welding of assemblies requires means for locating the parts to be joined by welding in the required position and relation to assure uniformity of size, shape and position of the component parts in the welded assembly (such as shown in Fig. 1).

It is well known that welding in the flat or down-hand position is easiest, most economical and conducive of highest quality welds. Further, the availability of electrodes specifically designed for flat or down-hand welding (Classifications E6020 and E6030—A.S.T.M.-A.W.S. Specification A233–42T) has made it highly desirable to position work for flat welding. To aid in the accomplishment of this end several manufacturers have placed weldment positioners on the market in recent years. Each positioner is essentially a work table to which the assembly is fastened by clamps, T-bolts, etc. The table is movable generally in two planes, i.e., it may be swung through an arc of about 180° on a section of a gear and it may also be rotated about its axis. This permits of locating all the welds in the flat position with a minimum of handling.

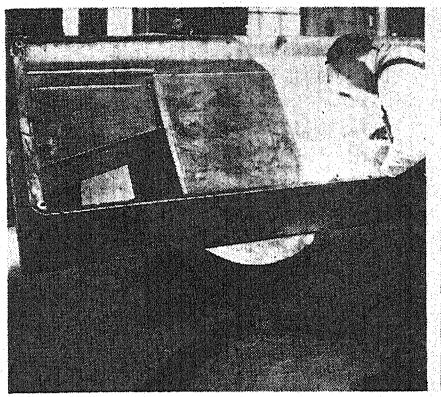


Fig. 3

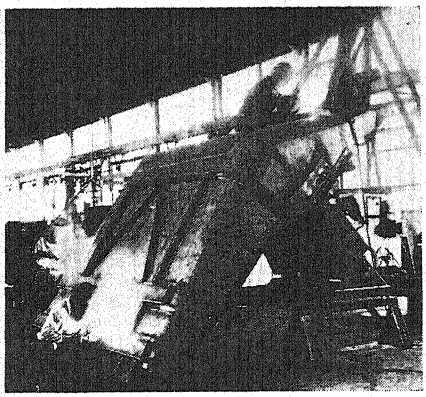


Fig. 4

Fig. 3—Weld Positioner Holding a Machine Base So That Operator May Weld in Flat Position

Fig. 4—Skip Bucket Held on Positioner While Three Operators Weld Simultaneously

In Figs. 2, 3, 4 and 5 several of the commercial models of positioners are illustrated. Figure 2 shows the essential construction features including the two motors, one for table tilting and the other for table rotation. Note the large semi-circular gear which tilts the table. Control equipment for the operator's use is also visible. These positioners are also available in manually and air-operated models. Figure 3 shows an operator welding on a machine base held in a positioner; note that the welding is in the "down-hand" position. Three operators welding simultaneously, in the flat position, on a "skip" are pictured in Fig. 4. In this case the positioner is raised off the floor on horses to permit swinging the large assembly, yet these horses are not fastened to the floor because care in the design and balance of the positioner permits ready handling of large overhanging loads. The details of a large capacity positioner are clearly illustrated in Fig. 5. This design will accommodate assemblies up to 14,000 pounds weight.

Weldment positioners, however, need not be elaborate, complicated

machines; frequently simple devices may be fabricated in a shop to accomplish the same purpose. Two such positioners are shown in Figs. 6 and 7. The former is a rotatable table mounted on wheels on a track and is used in hard-facing coal cutter bits. The latter is a simple turntable also used for positioning coal cutter bits for hard-facing.

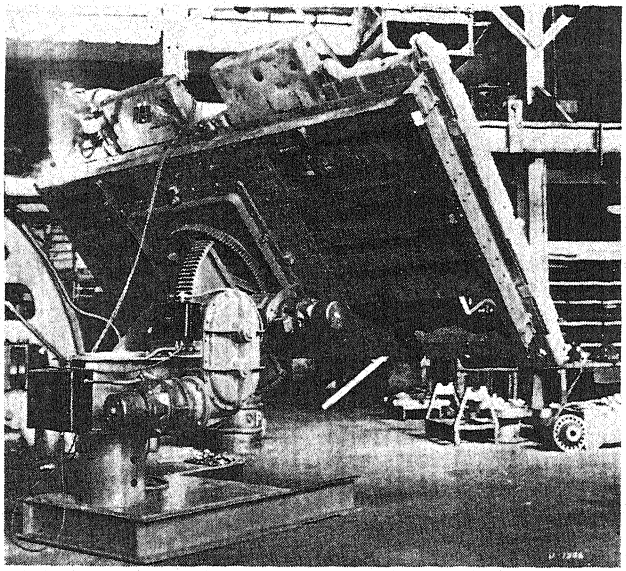


Fig. 5—A Large Weld Positioner Capable of Handling Assemblies Up to 14,000 Lb. in Weight

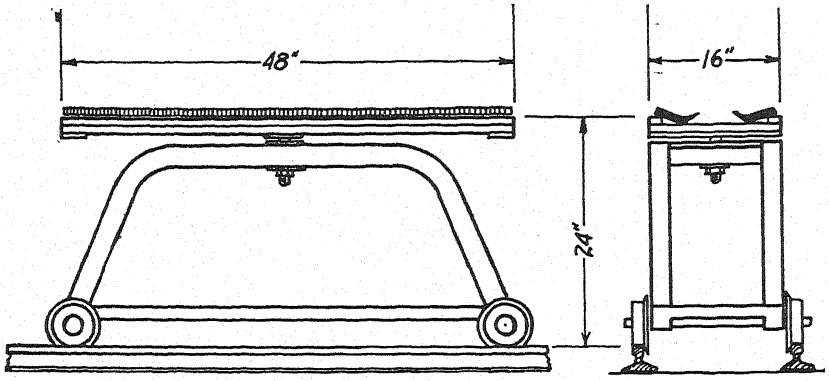


Fig. 6—Designed Particularly to Hold Parts in a Level Position Convenient for Welding and So That the Work Surface Is Capable of Rotation in the Horizontal Plane This Welding Jig Is for the Hard-Facing of Coal Cutter Bits

Tack-welding jigs (Figs. 8, 9 and 10) used in laying transmission pipe lines to assure concentricity of the adjoining pipe ends and good alignment are essentially welding jigs, although discarded immediately after the tack welds have been made. The fact that the pipe ends no longer require the support of the jig during the welding operation means simply that the function of the jig has been transferred to the tack welds.

Welding jigs are not always enveloping or exterior structures. They may take the form of simple separators of H-sections (Fig. 11) placed between the weld edges to prevent sheets in process of welding from overlapping or becoming "wapper-jawed," or of a dowel pin fitted in bored holes to preserve a true axial alignment in the component parts of a broken shaft.

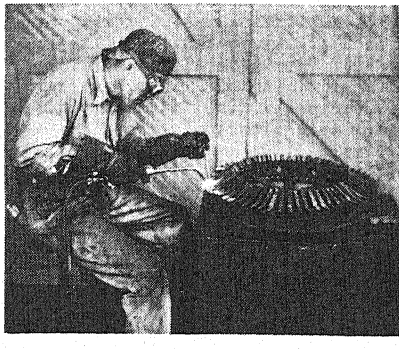


Fig. 7

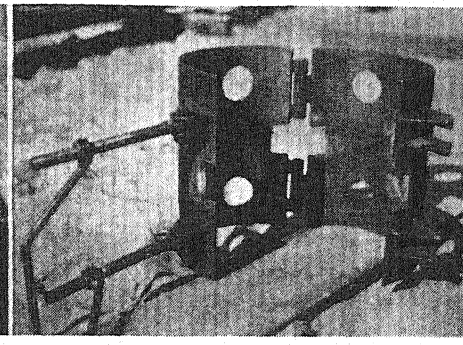


Fig. 8

Fig. 7—Convenient for the Operator, Correct Welding Position and Rotating Work Surface Combine to Make This Coal Cutter Bit Hard-Facing Jig Ideal in Design

Fig. 8—A Typical Jig for the Alignment and Tack-Welding of Pipe Sections. Note Particularly the Means for Quickly Putting the Jig in Position, the Extension Handles for Rapid Clamping and Tightening of the Jig and the Open-End Slots for Reducing the Clamping Adjustments to a Minimum

The dowel-pin method is sometimes employed in welding broken shafts of stone crushers and similar equipment to assure practically perfect alignment of the bearings on the opposite ends when welded. The broken shaft pieces are set up in a lathe, centered and accurately bored for the reception of a pin or dowel. The dowel pin to be inserted is turned oversize to make a press or shrink fit. The shaft pieces and dowel are then assembled by pressure, by heating the shaft section, or by cooling the dowel with solid carbon dioxide or liquid air. Then the assembly is welded or braze-welded while supported on the lathe centers. Care is taken to turn it as the welding proceeds and to check or correct the alignment during the welding process. The shaft is kept turning until nearly cold to prevent sagging out of line due to its weight.

A device for assembling large formed plates (Fig. 12) consists of parts welded to a steel floor plate into which the flat plate with the ribs and circular wall, previously welded, are placed. Note the use of screw jacks for forcing the parts into alignment.

In Figs. 13 and 14 are shown locating or indexing devices for positioning various elements of the assembly.

Welding Machine Jigs

Another type of welding jig, actually a machine, is the tube welding machine (Fig. 15) which provides a welding torch for heating the opposite edges of an open tube formed from skelp, and a rotating disc engaging the open slot in the formed tube to position the seam and keep it in line with the torch. Rolls propel the tube beneath the torch and compress the hot metal to make a pressure weld.

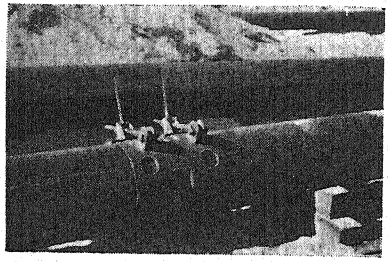


Fig. 9—Another View of the Tack-Welding Pipe Jig Shows the Pipe Lined Up and Held in Position. The Long Handles Attached to These Tightening Screws Make It Easy for the Operator to Apply Plenty of Pressure for Tightening the Clamps Without Hurting His Hands and Without Loss of Time

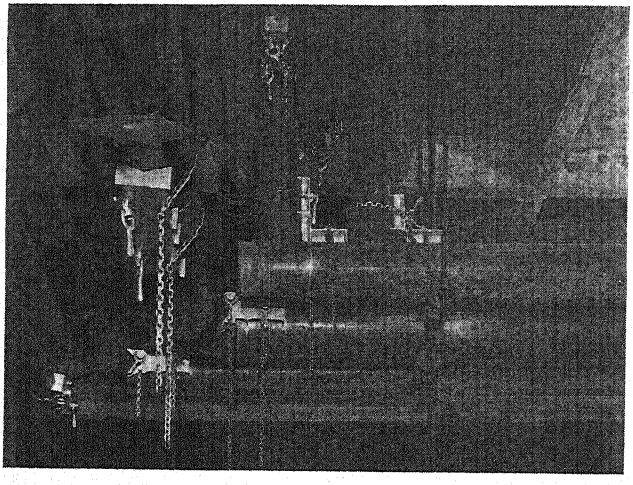


Fig. 10—Typical Patented Line-Up and Tack-Welding Jigs for Industrial Piping. The Clamping Arrangement in This Case Consists of Lengths of Chain with a Long Handled Nut and Screw Arrangement at the End of Each Chain. The V-Block (See Fig. 21) Locating Method Is Utilized

Tube welding with automatic electric welding progresses in a somewhat different manner. The tube is held stationary and an automatic welding head travels on an overhead track above the work. Rolls are not essential for this process; ordinarily simple clamping jaws are used instead.

The same type of machine has been employed to operate a separate welding jig that holds a tapered tubular shape. In this case the rolls

propel the jig beneath the torch and provide the compression required to make a pressure weld.

Reasons for Use of Jigs

From this brief analysis, the following reasons may therefore be offered for the use of jigs for welding of sheet metal and other assemblies. These are arranged in what appears to be the order of relative importance:

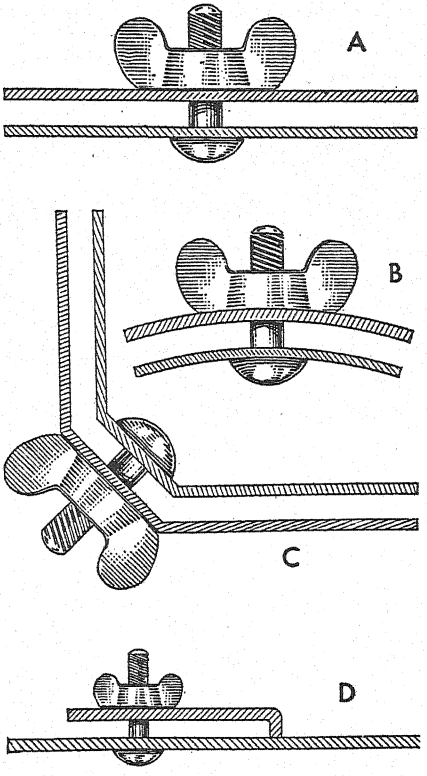


Fig. 11—The H-Clamp Is a Handy but Simple Modification of the Simple Strap Type Clamp. Several Variations to Take Care of Various Sheet Metal Contour Conditions Are Shown Here

1. To eliminate or control warping, crawling, buckling and distortion due to heat effects in the work parts by absorbing and dissipating heat into the jig structure, or by physical restraint.

2. To locate the parts to be joined by welding in the required position and relation to assure uniformity of size, shape and position of the components when assembled by welding.

3. To hold parts in position for welding or hard-facing convenient to the operator so that his efforts will be expended to the best advantage.

4. To so prepare broken parts by machining that correct alignment will be assured by means of dowels or other devices, as in the case of broken shafts.

Spacing

Displacement of the welding edges when heated for welding takes two forms. The first is the purely local expansion of the hot metal substantially in the plane of the sheet, and the second is a slight curvature of the metal away from the weld zone due to the local expansion or wedge effect of the

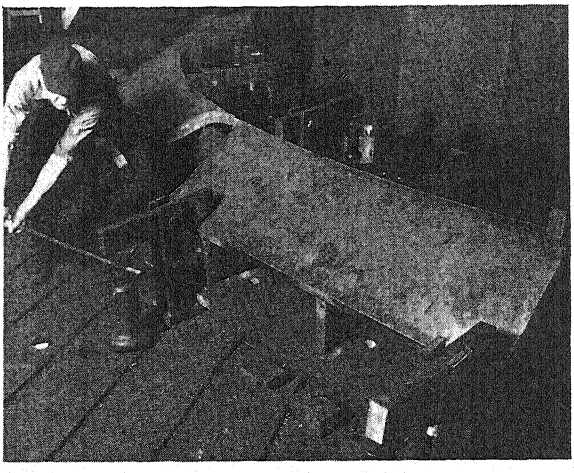
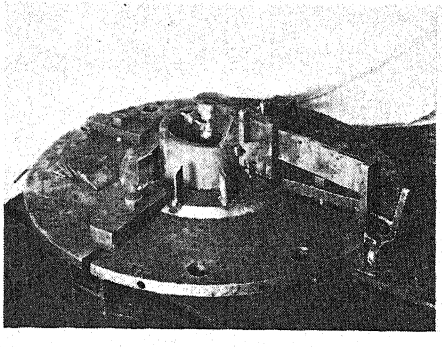


Fig. 12—Shows an Assembly Fixture for Large Formed Plate



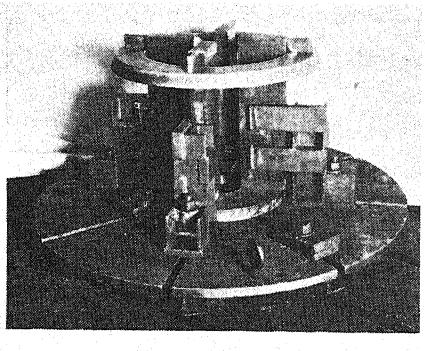


Fig. 13 **Fig. 14**

Fig. 13—Illustrates an Indexing or Locating Fixture
Fig. 14—This Is Another Locating Fixture for Positioning a Number of Parts at Their Respective Points

hot weld area. The curvature of the material in its plane is resisted, of course, very strongly in sheet metal of some breadth with the ultimate effect of upsetting the hot metal and causing curvature in the reverse direction or toward the weld zone as the metal cools.

It is because of this upsetting tendency that an operator welding practically unrestrained edges often finds it convenient to start a butt weld with the opposing edges out of parallel an amount which varies with conditions (as in Fig. 16). For steel plate a standard usually quoted is $^1/_4$ in. per foot of weld length, but the allowance should vary somewhat with the metal whether steel, copper, bronze or Monel, also with the thickness of the sheet and the speed of welding and the means provided for clamping the edges and dissipating the heat. A rule for sheet metal that seems to work well is an allowance equal to the sheet thickness per foot of weld length.

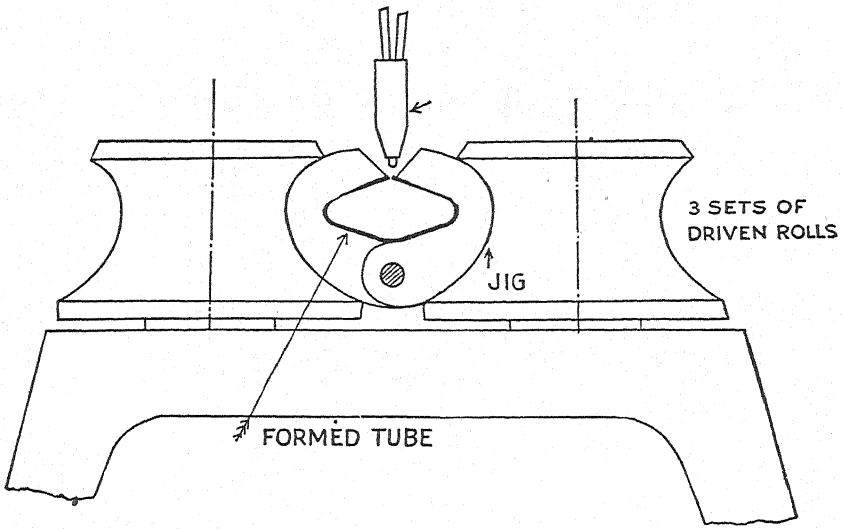


Fig. 15—For Making Sheet Steel Tapered Tubing of a Partially Diamond-Shaped Cross-Section by Machine Welding, an Interesting Jig Consisting of Formed Castings Was Developed. The Outer Sides Are Parallel, While the Inner Shape Fits the Tubing

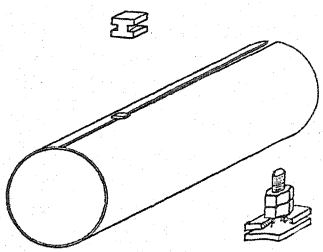


Fig. 16—A Spacer Method for Aligning a Sheet Metal Shell for Welding. The Spacer Is Shoved Along Ahead of the Welding Operation to Hold the Metal Edges Apart the Correct Distance as the Welding Progresses

Following this rule, the spread per foot would be $^1/_8$ in. for No. 11 U. S. gage.

A novel method of aligning tank walls and ends is illustrated in Fig. 17. The rolled cylinder is dropped into the frame and wooden wedges are employed to close the gap. The bar shown at the top left is hooked over one

extended end and the screw with a crank handle is used to bring the ends into alignment. Also shown are revamped C-clamps used to hold the abutting edges for tack welding.

Miscellaneous Devices

While they cannot, strictly speaking, be called jigs, there is a large group of miscellaneous holding devices consisting of such things as C-clamps,

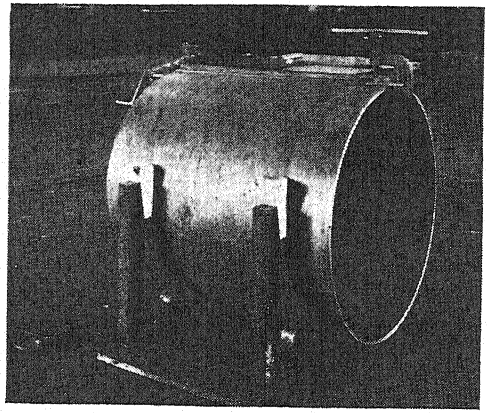


Fig. 17—A Simple Fixture for Aligning Tank Walls and Ends

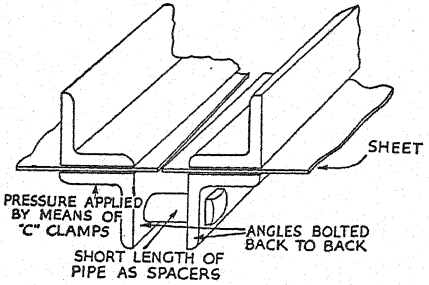


Fig. 18—An Interesting Use of Angle-Iron Bars Made Into a Jig for Welding Butt Type Seams on Sheet Metal. The Lateral Movement of the Sheet Is Retarded, and the Heat Is Absorbed by the Angles and Dispersed to the Air Thus Minimizing Distortion

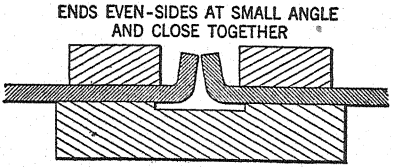


Fig. 19—Another Simple Method of Holding Sheet in Its Place for Making an Edge Weld. Angles Are Sometimes Substituted for Top Rectangular Bars

angle irons, rails, bars, cast or cut blocks, boxes of sand, simple levers, and simple wedges. These, because they form the most elementary type of device for holding parts for welding, should be considered in this discussion. They all find various uses as means for holding work in alignment, or in controlling the heat effects.

On the other hand, they are generally unsuitable for production work because of the fact that they take time and require hand adjustment. They are, in short, best suited for those jobs that occur only occasionally and do not warrant the fabrication of a better jig.

For spacing sheet metal and minimizing bulges and dents, lengths of steel shapes are frequently used (Fig. 18). Properly placed they retard lateral movement of the sheet and thus partially regulate the closing of the seam from the welding heat.

Similarly used for the same purpose are heavy bars (Fig. 19), strips of heavy plate, or other bulky sections of iron or steel placed along the seam.

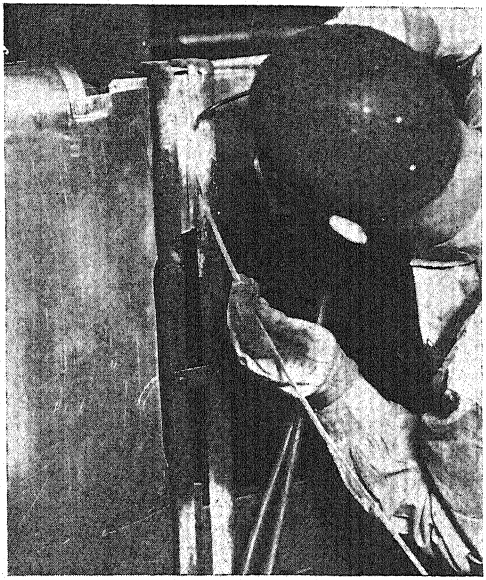


Fig. 20—Heavy Steel Plate with a Beveled Slot Down the Center Is Used for Joining Sheet Metal Panels of a Certain Type of Truck Body

When large and heavy enough and placed close enough to the seam they also serve to conduct some of the heat away from the sheet, which might otherwise go into the sheet and cause buckling or distortion.

When working on a production basis, particularly on short seams in light sheet metal, special jigging equipment is justified. This may take the form of cast members, which may be hollow and water-cooled, or simple sections of plate in which beveled slots are cut (Fig. 20).

V-blocks (Fig. 21) often are used for aligning and holding bars, tubing, small diameter pipe or members of curved, angular or irregular cross-sections. These blocks can be cast, or cut from heavy sections either with the gas torch or with a power saw. They should be accurately formed so that they can be used on a surface known to be level to give a true alignment.

For holding work to the surface of a table, to straight bars, to rail flanges or sections of angle iron, C-clamps (Fig. 22) are most useful. This simple device is quite handy for general work, but may be too slow for consideration for production work or for incorporation in a jig designed for mass production.

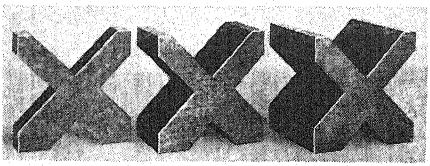


Fig. 21—A Typical Set of V-Blocks Fabricated from Steel by Flame Cutting

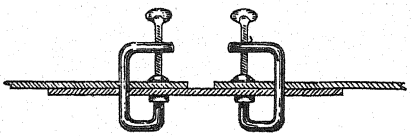


Fig. 22—The Familiar C-Clamp Finds a Multitude of Uses for Clamping and Holding Welding Work. The Principle of the C-Clamp Is Frequently Utilized in the Fabrication of Jigging Apparatus

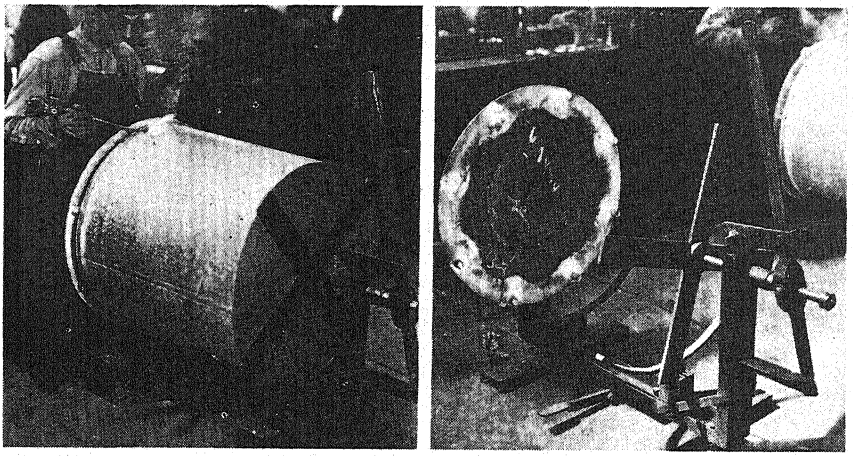


Fig. 23—This Jig for the Fabrication of Round Galvanized Containers Is Well Designed for Easy Operation, Holding Parts in Exact Position and for Convenience of the Operator. The Simple, Smooth-Working Clamping and Holding Arrangements Are Clearly Visible

Design Fundamentals

When starting out to design a jig for any given operation, there are certain fundamentals of design which should be carefully studied before actual work is begun.

(*a*) The economies to be derived from any jig must be obvious and apparent. The number of articles to be produced, the extent of work which the jig must do, whether or not it will be simply a holding device or will also have to perform a fitting function as well, are points in question. Thus the simplicity or complexity of the welding jig will bear on this point.

(*b*) The position of all locating points, their mechanical movements and the effect of the welding heat on them should be determined in advance. Visibility of these points to the operator is also important.

(*c*) The jig should work not only rapidly but easily and smoothly (Fig. 23). Daily output per operator depends largely on the ease of loading and handling.

(*d*) The welding jig should be designed so that the work can be inserted in the correct position only (Fig. 24).

(*e*) Make the use of the jig flexible by having locating points adjustable. Then rough work, or similar work of a different size can be handled easily on the same jig (Figs. 25 and 26).

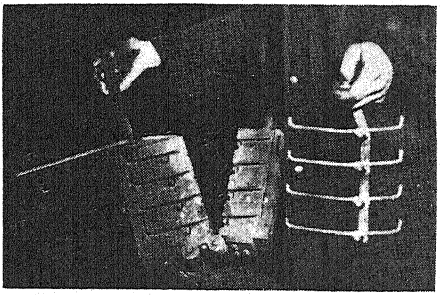


Fig. 24—This Simple Jig Has Been Designed Primarily So That the Work Cannot Be Inserted Out of Position

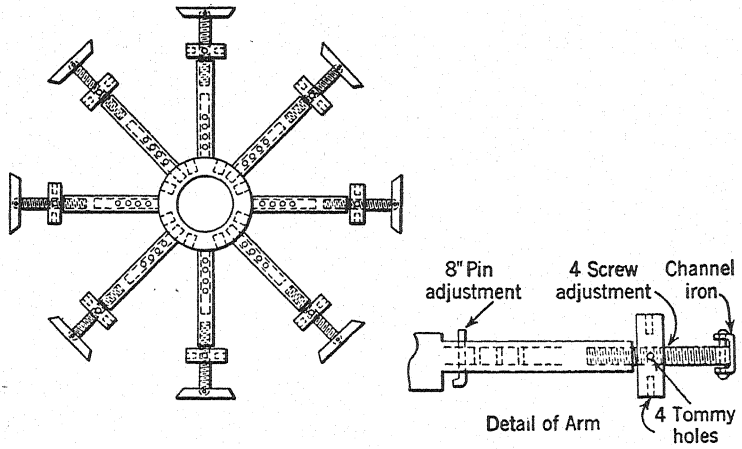


Fig. 25—This Is an Interesting Jig That Has Been Purposely Made Flexible to Handle Different Sizes of Work. It Was Designed for Holding Cylindrical or Octagonal Tanks from the Inside. Notice the Several Details Lending Flexibility, and the Secure Locking Arrangements in the Detail of the Arm

(*f*) Clamps should operate rapidly and easily. It is important that they be positioned away from the welding heat so that they will not overheat.

(*g*) Position each clamp opposite a bearing point to avoid springing the work. To avoid delay through loss or misplacement, make all clamps integral parts of the jig.

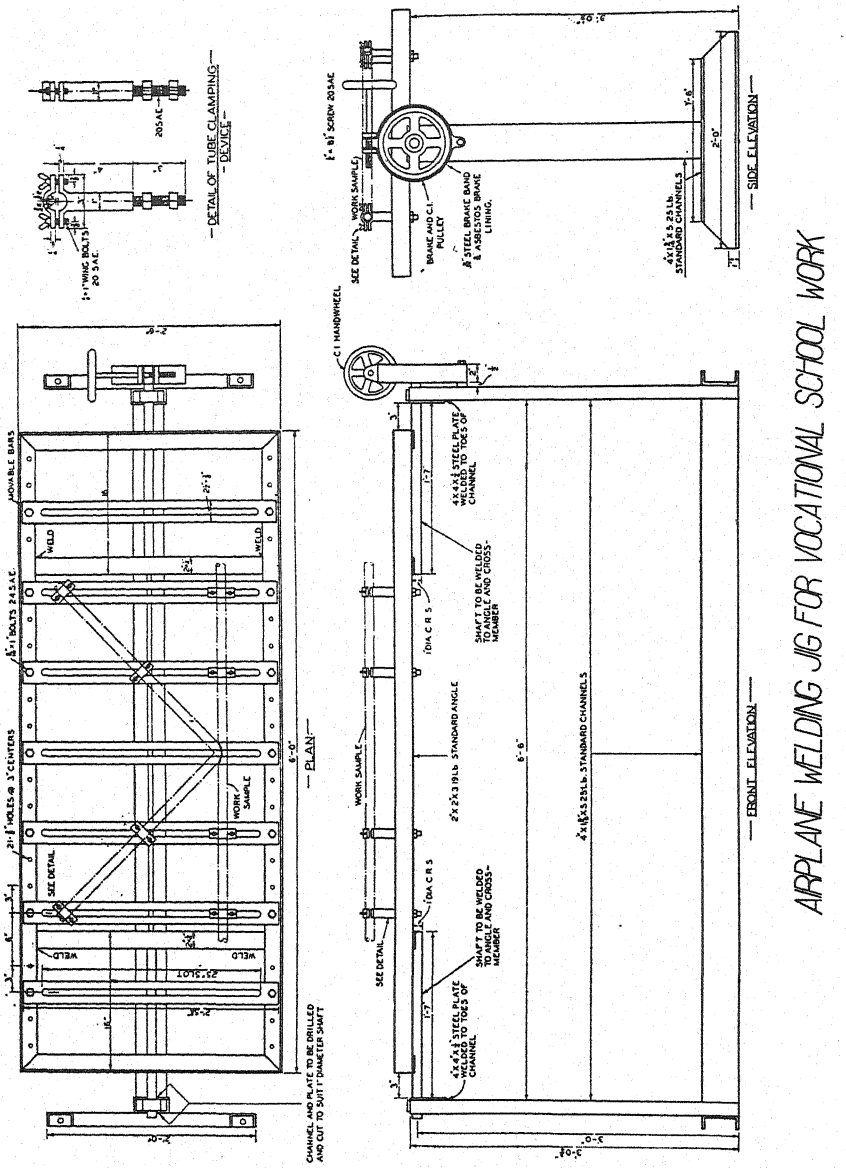


Fig. 26—Flexibility Is Exemplified in This Jig for Fabricating Aircraft Details in Tubing. The Work Frame Is Mounted at Table Height, and Can Be Revolved and Clamped in Any Position by Means of the Pulley, Brake and Hand Wheels at the Right. Seven Slotted Bars Are Provided and Additional Bolt Holes for Positioning Them Facilitate Ready Readjustment. A Number of Tube Clamping Devices, Shown in Detail in the Upper Right-Hand Corner of the Drawing, Go with the Jig Making It Completely Flexible. Any Small Assembly in Various Positions Can Be Clamped to This Frame

(*h*) The least weight consistent with the required strength and stiffness can be attained by designing jigs for fabrication by cutting and welding.

(*i*) Sharp corners or edges should be avoided to eliminate possible injury to the operator.

(*j*) Handles should be provided for adjusting the jig parts or for moving the jig from place to place.

(*k*) Allow for the control of heat both in the jig and the work (Fig. 27). Do not overlook the fact that the heat from welding will cause expansion in the metal of the jig as well as the work.

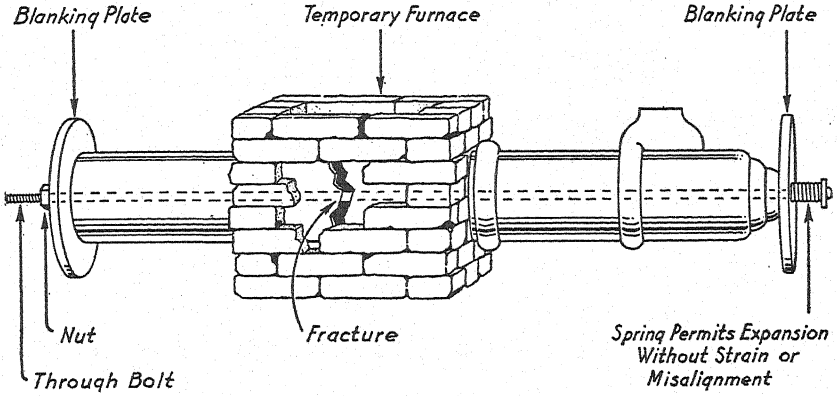


Fig. 27—The Device for Holding Broken Hydrants Together While Repairing Them by Welding Illustrates What Can Be Done in the Way of Allowing for the Control of Metal Expansion. The Jig Itself Consists of a Long Bar, Threaded at Each End, and Two Blanking Plates. The Spring at One End Between the End of the Bar and the Blanking Plate Permits the Tubular Hydrant Shape to Expand as It Is Preheated. The Spring Is of Sufficient Tension and Strength to Hold the Whole Assembly in Correct Alignment

Accurate Work Positioning Depends on Locating Points

Locating points may be guides by which to line up the outside edges of component parts of the work, or they may consist simply of holes cut or punched in the work previous to the welding operation for aligning the members by means of dowel pins. Whatever they are, their kind and number must be accurately determined. The nature of the work to be done will largely dictate the kind and number of points.

Pads, bosses, lugs, pins or studs, V-blocks, cup and cone arrangements (Fig. 28), screws which are either stationary or movable, finished holes, corners and edges, are the usual types of locating points.

All pins or studs that bear on the edges of the work should be flattened. A flat bearing surface wears well while a simple point does not.

Similar to V-blocks are cupped sections in the jig. If partial rotation of members before or during welding is important, dowel pins can be used instead. For locating concentric tubes or cylinders, the cup and cone arrangement is quite satisfactory.

Screws, if used for locating, should be long enough to project through

the walls of the jig. The ends on these may be conical, countersunk or flat. Occasionally it is desired to have the screws movable sideways or entirely floating for easy adjustment.

Whatever their use or construction, locating points must be firm and rigid in whatever position they may be. They may be cast solid with a jig body, permanently fixed to it, or adjustable. Set screws with check nuts are handy. Standard squareheaded or headless screws with a screw driver slot in the upper end are advantageous at times. In this connection, set

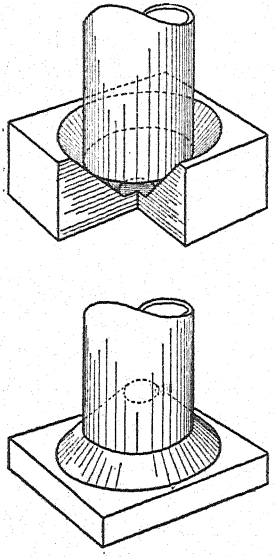


Fig. 28—The Cup-and-Cone Devices for Locating Concentric Cylindrical Parts of Work. They May Be Cast Into the Jig or Attached Separately

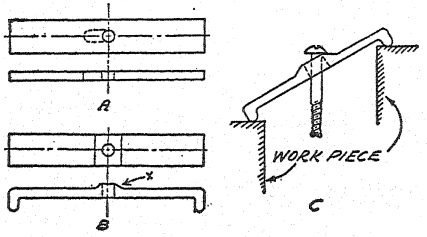


Fig. 29—The Simplest Type of Clamping Device Is the Strap. Upsetting the Ends, and Incorporation of a Boss Through Which the Fastening Screw Rides, Permits Greater Flexibility of Position

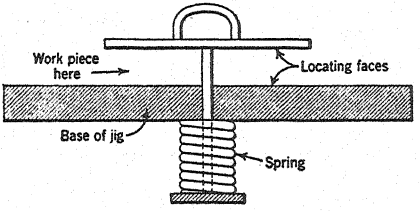


Fig. 30—Another Type of Strap Clamp. The Spring Arrangement Allows for Fast Application of the Clamp as Well as for Expansion of the Metal While It Is Being Welded

screws or check nuts should be used only for locating, and not for binding or tightening the work in the jig.

Finished holes, corners or edges as a means of locating have a very definite place in the scheme of jig design. These are usually located in the parts of the work to be assembled, and in the case of production operations can usually be depended upon to be in exactly the same position on each job that comes through. If the corners or edges are only rough cut, of course, they cannot be used for locating because they will vary in size. Accuracy, therefore, would not be accomplished.

In all cases, while accuracy is important in the placement and fixing of locating points, there should be sufficient tolerance in every point to accommodate permissible variations in the work.

For Holding the Work

Clamping devices, many types of which are illustrated in this chapter, are of the utmost importance in the correct design of jigs. The efficiency of the whole operation may depend upon their design and upon the type of arrangement which secures the work in place.

Simplicity, positiveness of action, minimum adjustment, and attachment to the jig body should be accomplished if possible. As few operating screws or handles should be used as will accomplish the purpose. It takes time to screw even one or two turns per operation. Clamping screws should be long enough and conveniently located for easy, quick operation. They should be of sufficient size (Figs. 8 and 9) to prevent tiring the operator because of pressure required for manipulation. They should provide suffi-

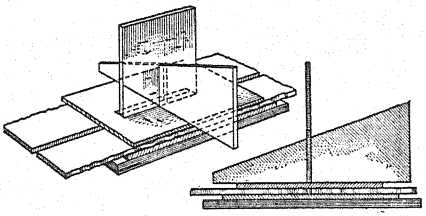


Fig. 31—The Wedge Principle of Clamping Is Illustrated in This So-Called "Double L-Clamp" Most Frequently Used for Holding Plate Edges Together in the Fabrication of Tanks and Vessels

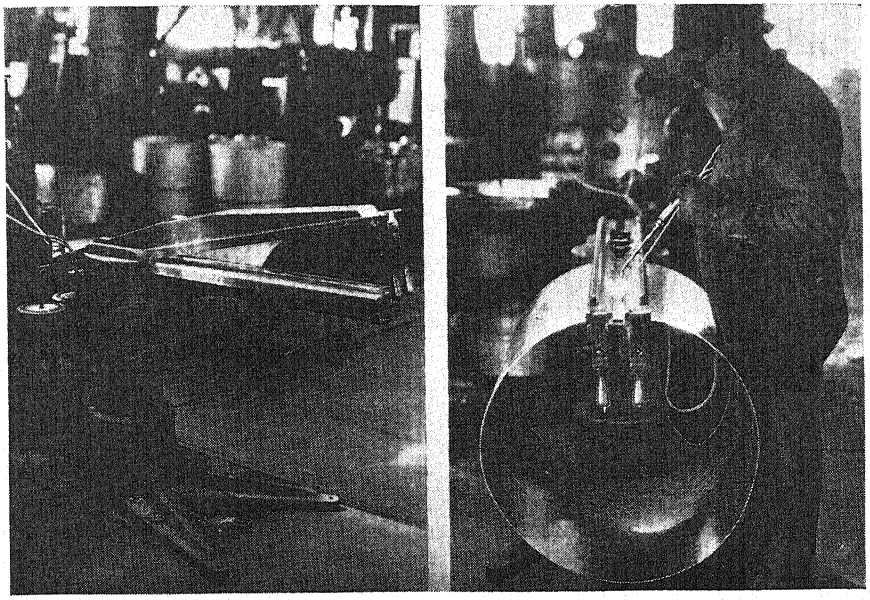


Fig. 32—The Swinging Leaves Type of Clamp Is Illustrated Here in the Horn and Anvil Type of Jig. This Is a Typical Arrangement for Holding Sheet Metal in the Fabrication of Tanks and Containers. Notice the Quick Acting Tightening Clamp at the Ends of the Bar Clamps

cient leverage on the handle so that it will not be necessary to use "persuaders."

To avoid a tilting tendency, a clamping pressure should always be exerted in a direct line against some solid point of support in the jig.

Clamps, if made of metal, expand and contract from heating and cooling. They, therefore, should be placed as far as possible away from the welding position. If in a position where they will become overheated, their expansion should be allowed for. It is most important that the gripping or locking part of the clamp should not be submitted to overheating.

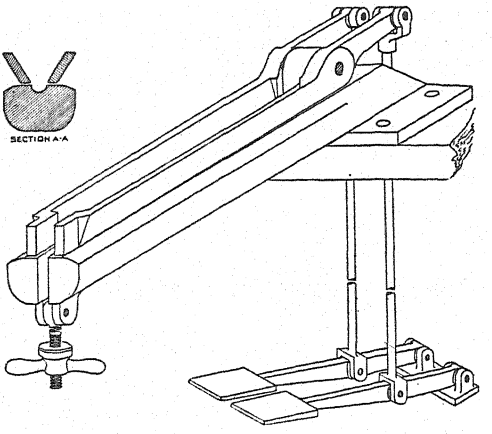


Fig. 33—Another Type of Stake, Horn or Anvil Jig for Steel Barrel and Cylindrical Container Fabrication. A Screw Type of Clamping Device Is Utilized in This. The Cross-Section in the Left-Hand Corner of This Illustration Shows the Use of Heavy Cast Iron Sections for the Dissipation of Heat. The Groove Directly Underneath the Welding Seam Permits Concentration of the Heat Where It Is Wanted—Namely, on the Seam

Types of Clamping Devices

Clamping devices are of four types: straps, leaves, wedges or gibs, and eccentrics.

The simplest type is the ordinary strap. This may be merely a strip of steel or it may be much more complicated. The simplest of all is a strip of metal with a hole in the center (Figs. 29 and 30) through which a bolt passes to give it pressure. Round or elongated holes allow for positioning. There are, however, obvious deficiencies in this simplest type. Too much pressure on the screw, for instance, will cause the outer ends to give

There are many modified and improved forms of this simple type. They all have their place, and even the simplest form is of value under certain conditions.

One of the most interesting variations to the simple strap is known as the H-clamp (Fig. 11). Where firm pressures are necessary, as for holding light sheet metal work, these are unequaled. They can be either flat, curved or modified as needed. The double L-clamp (Fig. 31) is also a variation, combining features of both the strap and wedge types. This device is sometimes referred to as the wedge or taper gib clamp. The specific needs of the work will more or less dictate the necessary deviations in adapting these clamps to given operations. These are particularly useful where access to the reverse side of the seam is difficult. They have found wide use in the fabrication of pressure vessels and large tanks and containers.

Another variation of the strap is that in which the ends are fastened and the center, by means of an adjusting screw, is used for a bearing point on the work. There are several types of this, varying according to need.

Swinging leaves, a second useful type of clamp, are particularly designed for simple and extremely rapid insertion or removal of the work. Various trigger lock devices at the open end have been designed which eliminate adjusting screws. An illustration of this is found in Fig. 32.

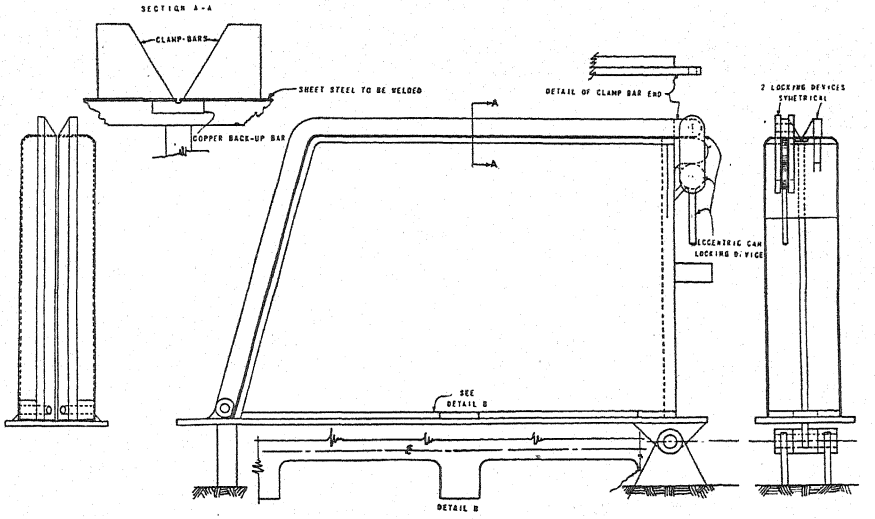


Fig. 34—An Adaptation of the Stake Type of Jig to Accommodate a Weld in Two Planes on Sheet Metal Stampings

The outstanding jig utilizing these elements is the stake, horn or anvil consisting essentially of a horizontal arm supported by post, column or wall at one end, the rear, and two-quick-acting clamps lying lengthwise of the arm on top, and pivoted at the rear end (Figs. 32 and 33). The clamps sometimes are counterbalanced by weights or springs, and provided with pedals for foot operation. The clamping arrangement at the front end is of the quick-acting type easily and quickly applied and released.

This jig is the type employed for welding the longitudinal seams of barrels, drums, water heaters and similar containers made of sheet steel,

copper, brass, bronze, nickel and Monel. It serves to hold the rolled shape at convenient welding height and provides the means for clamping the sheet edges in the space relation required to compensate for contraction due to cooling as the weld progresses. Absolute restraint of the edges is, of course, impossible, hence a moderate degree of lateral movement is possible, thus tending to minimize the possibility of the weld cracking. The clamps and stake absorb excess heat and dissipate it to the surrounding air. In some cases water cooling is provided, but this feature is not common.

An adaptation of this stake type jig to the specific problem of welding buckets for a continuous conveyor is illustrated in Fig. 34. These buckets are fabricated of sheet metal and consist of two halves made as stampings.

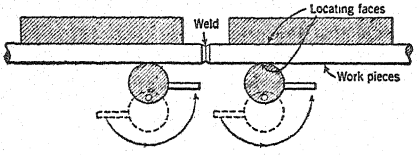


Fig. 35—Fast and Accurate Clamping Is Obtainable Through the Typical Cam and Lever Arrangement Shown Here

The weld lies in two planes along the bottom and one end; the other end and top are open. Bent stakes are provided to hold the abutting edges in the two planes. While at first observation the 3-in.-thick beveled bars for the stakes may appear heavy, it is interesting to note that on the actual application they were necessary. Jigs of this design were successfully used on a production order of 15,000 units. The eccentric clamping elements (discussed later in detail) proved very satisfactory.

Eccentric clamping arrangements provide great ease of insertion of work and removal of work without the necessity of screwing down bolts for tightening purposes. There are two types of these, the eccentric shaft and the eccentric lever (Fig. 35). Both have greater use for locking purposes than for any other. The eccentric shaft, for instance, is arranged so that a half turn causes the wider portion of the shaft to bear on a connecting rod, thus exerting pressure. This is useful mainly for very fine adjustments, as the throw is only about $^1/_{16}$ to $^1/_4$ in. Figure 36 illustrates the application of this principle in bringing a rolled ring to size and clamping for tack welding. This jig was assembled from a few pins, some short round scrap ends and the inside of a motor frame.

Welding jigs are a vital part of aircraft manufacturing procedures. In Fig. 37 is pictured a jig which holds the motor mount ring while the forgings, to which is attached the engine, are welded to it. Extreme accuracy is necessary in this work. Stainless steel pads are welded to the center plate of the jig to give long life at those points where the flame strikes. Note the various types of clamps employed on this jig.

Controlling Expansion and Contraction

Any jig for welding work should preferably be designed so that it will not become heated or, if this is unavoidable, so that locating points and other parts can be adjusted accordingly. This expansion and contraction problem, if it cannot be eliminated completely, can be handled in one of four

ways. The expansion can be controlled in part; it can be completely resisted; the right amount of heat can be carried away by correct design of the jig so that there will be no effect on the work itself; or a close control of the welding operation to minimize the heating effect can be accomplished. There is, of course, considerable overlapping of these four factors.

In light work, the heating effects may be resisted completely. The welded seam itself then takes up the force of expansion. Obviously, a

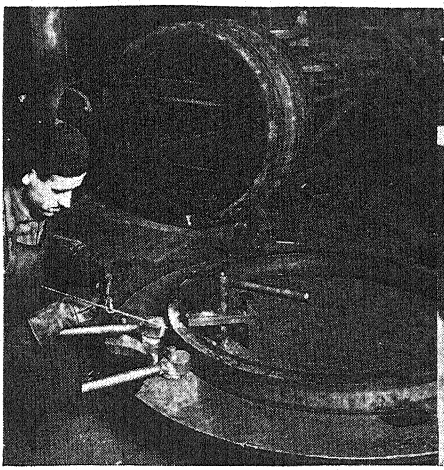


Fig. 36

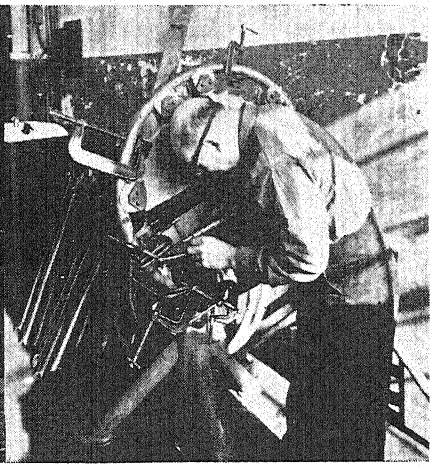


Fig. 37

Fig. 36—A Typical Fixture Employing the Cam Lever Method of Holding
Fig. 37—Jig for Holding Aircraft Engine Motor Mount Ring and Attachment Forgings During Welding

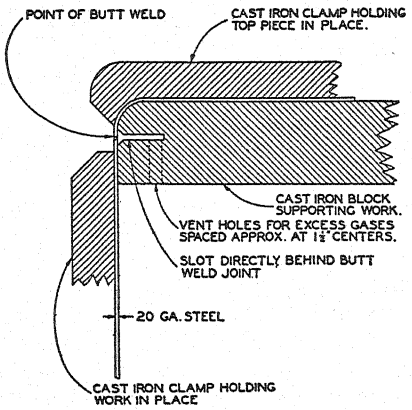


Fig. 38

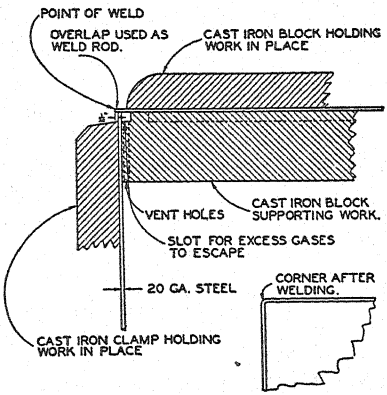


Fig. 39

Fig. 38—Jig Parts for Making Butt Type Welds
Fig. 39—Jig Parts for Making Square Corner Welds

strong device is required to accomplish this. Actually, complete resistance to the action of heated metal is practically impossible, particularly in heavier work and to resist it is not always the best method of minimizing distortion. Some jigs carry away sufficient heat and at the same time resist the expanding action so that little distortion takes place (Fig. 38). Cast metal parts, some of them water-cooled, may be necessary to absorb the heat rapidly.

Construction of liners for refrigerators illustrates this type of jig design. The liners require either square or rounded joinings of the sides, and of the bottom with the sides. Figure 38 shows a liner of the rounded corner type

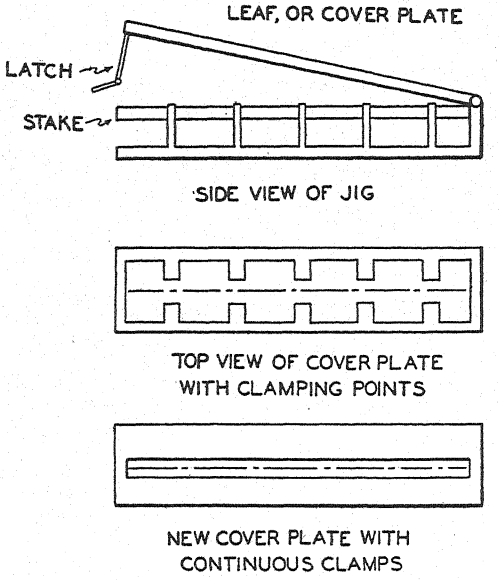


Fig. 40—An Interesting Illustration of the Redesign of a Jig to Overcome Certain Defects That Were Discovered in the Original Design

being welded, the jig itself and the location of the butt weld. Observe the venting slot and holes for the relief of gases released under the weld which if confined would cause defects in the welded seam.

Figure 39 shows details of the square joint made with a similar welding jig designed for holding liners with the sides and bottom at right angles at the intersections. In this case the sides are so held that one overlaps the other sufficiently to supply the requisite welding material to make the weld. This when finished is as shown in the small detail. Again, a slot for venting gases collecting beneath the weld is provided which also provides space insulation that prevents too rapid absorption of the welding heat. (Figures 38 and 39 are taken from the paper by J. H. Blaha, presented at the October 1935 meeting of the American Welding Society.)

Figure 40 shows a welding jig that proved unsatisfactory in service which is used here to illustrate the importance of heat absorption capacity.

Mechanical restraint alone will not prevent warping and buckling of thin metal if the jig does not provide for absorption and dissipation of excess heat. The jig was made for welding light sheet metal cans triangular in cross-section. Trouble was caused by warping and buckling when welding the longitudinal seam in the center of one of the three sides due to lack of material in the jig and to the fact that the clamping was restricted to five points on each side of the weld. The defect was corrected by replacing the jig cover with one that provided for continuous clamping on each side of the seam. The stake was made of substantial cross-section with a narrow groove in the center, which assured an effective chill for the under side of the seam.

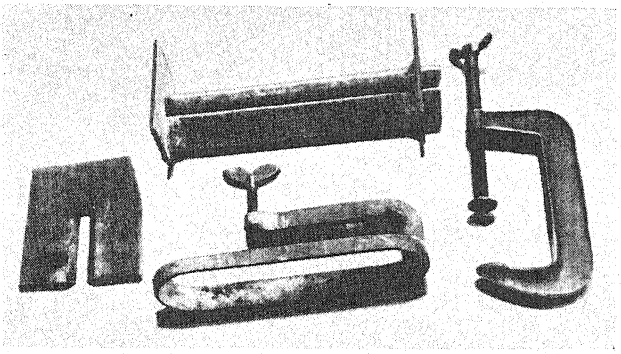


Fig. 41—Typical Clamp and Chill Plates Used in the Fabrication of Stainless Steel Sheet Metal Production Work

Control of the oxyacetylene flame itself is probably one of the best ways of controlling the heat from welding operations. The use of the smallest possible flame consistent with good work, a welding rod with a lower melting temperature than the base metal (such as bronze welding rod), or a technique for rapid welding (such as back-hand technique with excess acetylene flame) may help considerably to eliminate distortion. Individual requirements for the job will often show a way for accomplishing this. The correct type and size of welding tip, exact gas pressures, and the various phases of good welding technique must be understood in order to be successful.

Welding Jigs for Corrosion-Resistant Metals

Stainless steels and corrosion-resistant metals in general are more expensive than carbon steels, and are used mostly in the thinner gages to reduce costs. It is important as a rule that all joints be welded with rods of the same materials, or with rods specially designed for the particular type of alloy steel, in order to provide and maintain corrosion-resistant characteristics throughout. Welding jigs must be used on production jobs as a rule to secure uniformly satisfactory work at a reasonable price.

This applies particularly to the 18–8 chromium-nickel type of austenitic stainless steels. Thermal conductivity is only about 40% that of mild steel while the coefficient of expansion is about 50% greater. These characteristics introduce greater creeping and crawling effects than would be met on low carbon sheet steel when being welded. Hence, will be seen the great importance of control by manipulation and the use of suitable jigs. Welding jigs for these metals must not forcibly restrain expansion and contraction because of the probability of causing buckling or cracking in the welds. They must be so constructed as to absorb and dissipate excess heat without setting up injurious buckling or tension stresses (Fig. 41).

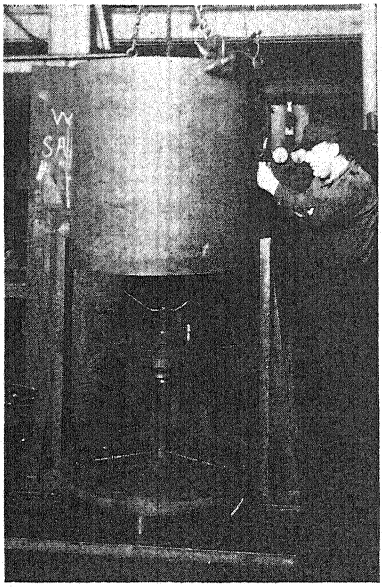


Fig. 42—This Assembly Fixture Is Used for Attaching the Tank, the Assembly of Which Is Illustrated in Fig. 17 to the Ring Shown in Fig. 30. Moving Plungers Actuated by Screw Whose Handle Can Be Seen Just Under the Tank, Position the Tank Centrally on the Ring. Bars of Steel Are Evenly Spaced About the Inside Diameter by Means of the Swinging Arm Which Is Indexed Around by Means of a Drilled Disc and the Removable Dowel

Jigs for Sheet Aluminum Alloys

Welding jigs properly designed and used actually make possible successful welds in metal alloys of such critical characteristics when heated to fusion temperature as to be practically unweldable otherwise. In the case of a certain aluminum alloy which is quite weak and brittle at welding heat, the jigs used in welding bus body panels must be so designed as to restrain the metal very lightly or not at all on one side of the seam. They must also abstract a minimum of heat from the sheet near the weld because of high heat transmission of the alloy and consequent heat loss and chilling effect on the welding zone.

Thus, in some cases it would appear that anomalous conditions must be met with means that seem quite contradictory to the basic principles established for welding jigs designed for mild steel and other common commercial sheet metals. Instead of providing for maximum heat absorption

for this alloy, the points bearing tightly are shielded with asbestos pads to reduce the heat loss.

Aluminum and its alloys play important parts in aircraft construction. Figure 44 shows the tack welding of an aluminum alloy air duct, while the previously stamped sections are held in the jig. A large number of small tacks at frequent intervals are used on this part to hold the pieces in proper alignment. Actual welding is performed on the assembly outside the jig since restraint during welding would adversely effect the results. This air duct is fabricated of 52S alloy (2.5% magnesium, 0.25% chromium) and is used for cooling oil.

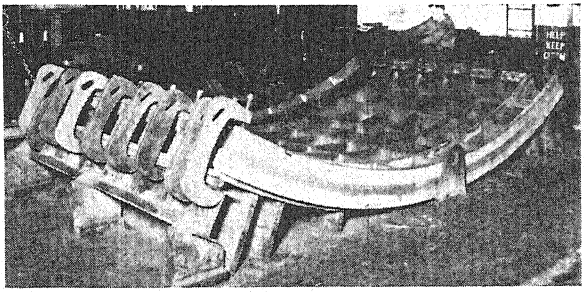


Fig. 43—The Large Assembly Fixture Shown Here Is Built on a Steel Floor Plate for Assembling Large Rolled Segments Into a Heavy Cylindrical Wall. Each Rib Comes to This Jig with Its Spacers Welded in Place So That the Rolled Ring Segments Are Self Spacing

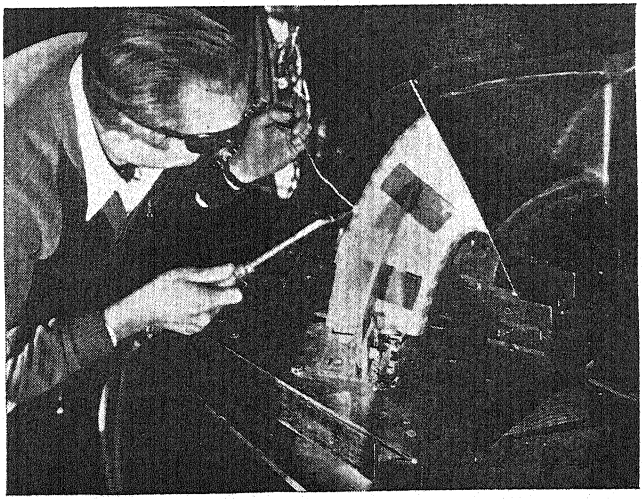


Fig. 44—A Typical Jig Used for Tack Welding an Aluminum Alloy Air Duct for Aircraft Use

Heat Expansion

Expansion of sheet metals held in jigs must be provided for to some extent, because not all the excess heat can be absorbed and dissipated by the jig body, nor can more than moderate restraint be imposed to prevent heat movements. One of the most important functions of a welding jig as a rule is to hold the welding edges in the same plane, and movements that do not defeat this purpose often can be accepted. The following table offers convenient expansion data for the designer:

Approximate Total Expansions of Metals with Heat Between Room Temperature and Temperature in Table*

	Expansion					
	500°F.		1000°F.		1500°F.	
	In. per In.	In. per Ft.	In. per In.	In. per Ft.	In. per In.	In. per Ft.
Aluminum	0.006	0.074	0.012	0.148	Melts at 1218°F.	
Brass	0.005	0.057	0.010	0.115	0.014	0.172
Bronze	0.005	0.058	0.010	0.118	0.015	0.176
Copper	0.004	0.053	0.009	0.106	0.014	0.159
Iron, Wrought	0.003	0.039	0.006	0.078	0.010	0.117
Iron, Cast	0.004	0.045	0.007	0.090	0.011	0.135
Lead	0.007	0.090	Melts at 621°F.			
Monel	0.004	0.044	0.007	0.088	0.011	0.132
Nickel	0.003	0.042	0.007	0.085	0.011	0.127
Steel	0.003	0.038	0.006	0.076	0.010	0.116
Steel, Stainless	0.004	0.056	0.010	0.112	0.014	0.168

* Expansion rates vary with temperatures. Expansions per inch and per foot are approximate averages.

CHAPTER 33A

STANDARD METHODS FOR MECHANICAL TESTING OF WELDS*

Scope, Testing Procedure, Nomenclature, Etching, Base Metal, Weld Metal, Welded Butt Joints, Fillet-Welded Joints, Testing Spot Welds

FOREWORD

AS FOR any engineering product, the quality of welds depends upon competent inspection and adequate tests. Experience has shown that, in general, mechanical tests to determine their strength and other properties are the least expensive and most reliable tests for the quality of welds. Therefore, they are the tests most widely used. In addition, other tests are used in some cases. No other tests appear likely to replace mechanical tests entirely.

Mechanical tests for welds are similar to the usual mechanical tests for the base metal—plate, tubes, etc., with the changes which have been found necessary to determine the properties of welds. These tests for welds have now been used for a sufficient length of time to indicate quite definitely the properties to be determined and the test procedures which not only give adequate information as to the quality of the weld but are the most practicable for welded fabrications.

Although there is a surprising agreement among welding engineers on the properties to be determined and, in general, the test procedure, there is a wide divergence in the shape and size of the specimens and the details of the test procedure. This considerably increases the cost of making the tests, and decreases the usefulness of the results obtained under different codes and specifications, because they cannot be compared directly. There is no logical reason why for a particular welded fabrication the same size and shape of specimen and the same test procedure should not be used by every one. Standardization in this field has all the advantages to every one concerned that are so generally recognized in other fields and need not be discussed here.

Standardization of the mechanical tests for welds does not necessarily apply to research. It does apply to all tests during commercial production, i.e., what are often called "routine tests."

* Prepared by a committee consisting of M. F. Sayre, Union College, *Chairman;* L. M. Dalcher, American Welding Society, *Secretary;* Bureau of Ships, Navy Dept.; R. W. Clark, General Electric Co.; A. N. Kugler, Air Reduction Sales Co.; G. S. Mikhalapov, The Taylor-Winfield Corp.; J. F. Randall, Combustion Engineering Co.

GENERAL REQUIREMENTS

I. Scope

This standard gives the requirements for the specimens, the testing procedure and the method of obtaining the properties. It is not a specification promulgating required values of the properties. The persons including this standard as a portion of a code or specification for a welded product should state definitely:

1. **The one or more tests which are required.**
2. **The limiting numerical values of the properties and whether they are minimum or maximum.**
3. **The interpretation, if any, of the properties.**

II. Testing Procedure

All tests involving the application of a tensile load to a specimen shall be carried out in accordance with the applicable portions of "Standard Methods of Tension Testing of Metallic Materials," A. S. T. M. Designation E-8.

III. Nomenclature

The terminology used in this standard conforms to the "Standard Definitions of Terms Relating to Methods of Testing," A. S. T. M. Designation E-6, and to the standard of the AMERICAN WELDING SOCIETY, entitled "Definitions of Welding Terms and Master Chart of Welding Processes." The term "soundness" used in this standard means the degree of freedom of a weld from defects discernible by visual inspection of any exposed surface of weld metal. In preparing reports of tests made in accordance with this standard, nomenclature shall conform to the above standards and definitions.

IV. Etching

Specimens to be tested in accordance with this standard shall be etched for either of two purposes: (1) to determine the soundness of a weld (see Sec. VI, *B*), or (2) to determine the location of a weld.

For tests in which the dimensions of the specimen, the procedure or the results depend upon the location of the weld, the surface of the specimen at and adjacent to the weld shall first be etched with any reagent which makes the boundary between the weld metal and the base metal visible, if the boundary is not already distinctly visible.

NOTE: Some reagents commonly used for carbon steels and low-alloy steels (5% or less of alloying elements) are the following:

Hydrochloric acid—Equal parts by volume of concentrated hydrochloric (muriatic) acid and water. Immerse the welds in this reagent at or near the boiling temperature. Hydrochloric acid will etch satisfactorily on unpolished surfaces. It will usually enlarge gas pockets and dissolve slag inclusions, enlarging the resulting cavities.

Ammonium persulphate—One part of ammonium persulphate (solid) to nine parts of water by weight. Vigorously rub the sur-

face of the weld with cotton saturated with this reagent at room temperature.

Iodine and potassium iodide—One part of powdered iodine (solid) to twelve parts of a solution of potassium iodide by weight. The solution should consist of one part of potassium iodide to five parts of water by weight. Brush the surface of the weld with this reagent at room temperature.

Nitric acid—One part of concentrated nitric acid to three parts of water by volume.

Caution—Always pour the acid into the water when diluting. Nitric acid causes bad stains and severe burns.

Either apply this reagent to the surface of the weld with a glass stirring rod at room temperature, or immerse the weld in boiling reagent provided the room is well ventilated. Nitric acid etches rapidly. It should be used on polished surfaces only, and will show the refined zone as well as the weld metal zone.

After etching, the weld should immediately be washed in clear water, preferably hot water; the excess water should be removed; the etched surface should then be immersed in ethyl alcohol, removed and dried, preferably in a warm air blast. The appearance may be preserved by coating with a thin clear lacquer.

DETAILS OF TESTS

V. Base Metal

If there are specifications for the base metal, the tests of the base metal shall be in accordance with these specifications.

If there are no specifications for the base metal, the tests of the base metal shall be carried out in accordance with the standards of the American Society for Testing Materials. Tensile tests, if any, shall be in accordance with "Standard Methods of Tension Testing of Metallic Materials," A. S. T. M. Designation E-8.

VI. Weld Metal

A. Density

1. *Specimen.*—The specimen, *A*, shall be a cylinder complying with the requirements of Fig. 1, and consisting entirely of metal from the deposited metal zone. If the size of the weld is insufficient, the specimen may be machined from a test plate complying with the requirements of Fig. 2.

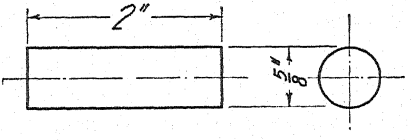


Fig. 1—Density Specimen *A*

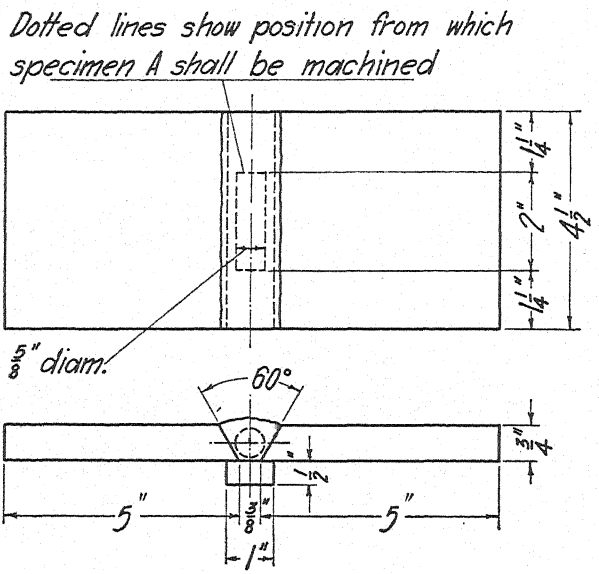


Fig. 2—Test Plate for Density Specimen *A*

2. *Procedure.*—After the specimen has been subjected to room temperature for not less than two hours, the average dimensions shall be measured (screw micrometer) to the nearest 0.0001 inch and the room temperature in degrees Centigrade shall be determined. Using a balance having an error not exceeding 0.0001 gm., the weight of the specimen in air shall be determined.

3. *Results.*—The density shall be computed using the formula:

Density, in grams per cubic centimeter =

$$\frac{\text{weight in air, in grams}}{\text{volume in cubic inches} \times (1 - 0.000033 \times t) \times 16.3872}$$

in which

t = temperature of specimen in degrees Centigrade.
16.3872 = number of cubic centimeters in one cubic inch.
0.000033 = volumetric coefficient of expansion of ferrous weld metal per degree Centigrade.

NOTE: The density is not an accurate measure of the soundness of weld metal. Voids or slag inclusions, scattered throughout the metal abundantly enough so that on an average straight line scribed on the face of the metal, one-twentieth of the length strikes voids, would result in a change in density of $(1/20)^3$ or one in 8000 (0.012%). To detect such a change calls for high accuracy of measurement. A further difficulty rises from the fact that the normal variations in density between different lots of sound steel may be themselves much greater than one in 8000.

B. Soundness: Etch Test[1]

1. *Specimen.*—A portion of the joint, specimen *B* (no figure) displaying a complete transverse section of the weld shall be removed by any convenient means such as trepanning, flame cutting, drilling or sawing. If removed by flame cutting at least 1/8 inch shall be machined from the face that sections the weld. This face shall be smooth, bright and polished.

NOTE: The face may be filed and polished with abrasive cloth finishing with grade 00.

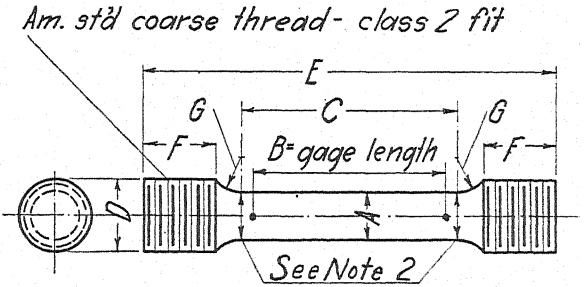
2. *Procedure.*—The face shall be etched. (See Note, Section IV, for suggested etching reagents.)

3. *Results.*—The etched transverse section of the weld shall be examined for soundness. (See Sec. III.)

NOTE: Persons writing codes or specifications should state definitely their requirements for soundness. Typical requirements are: "complete penetration," "no inclusions," "the number of gas pockets shall not exceed——per square inch," "no gas pocket shall exceed——inches in its greatest dimension," etc.

C. Tensile Strength

1. *Specimen.*—The specimen shall comply with the requirements of Fig. 3, specimen *C*-1 being used unless the size of the welded joint or deposited weld metal is such that a specimen of this size cannot be ma-

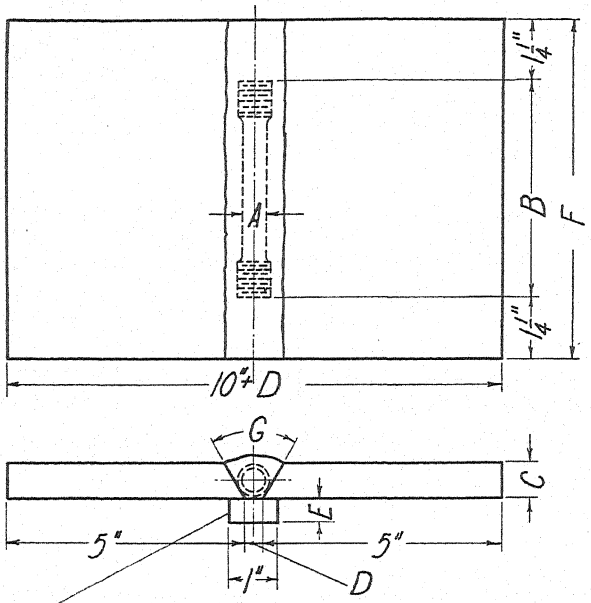


Specimen	Dimensions of Specimen						
	A, In.	B, In.	C, In.	D, In.	E, In.	F, In.	G, In., Min.
C-1	0.500 ± 0.01	2	2 1/4	3/4	4 1/4	3/4	3/8
C-2	0.437 ± 0.01	1 3/4	2	5/8	4	3/4	3/8
C-3	0.357 ± 0.007	1.4	1 3/4	1/2	3 1/2	5/8	3/8
C-4	0.252 ± 0.005	1.0	1 1/4	3/8	2 1/2	1/2	1/4
C-5	0.126 ± 0.003	0.5	3/4	1/4	1 3/4	3/8	1/8

Note 1: Dimensions A, B and C shall be as shown, but alternate shapes of ends may be used as allowed by ASTM Specification *E*-8.
Note 2: It is desirable to have the diameter of the specimen within the gage length slightly smaller at the center than at the ends. The difference shall not exceed 1 per cent of the diameter.

Fig. 3—All-Weld-Metal Tension Specimens *C*-1 to *C*-5, Inclusive

[1] See also Sections VII*A* and VIII*A*.



For gas welding, backing strip shall be omitted. Dotted lines show position from which specimen shall be machined.

Welding Process	Diameter of Electrode or Welding Rod, In.	Specimen	Dimensions of Test Plate and Tension Test Specimens						
			A, In.	B, In.	C, In.	D, In.	E, In.	F, In.	G, Deg.
Arc	Under 5/32	C-4	0.252 ± 0.005	2 1/2	1/2	1/4	3/16	5	45
"	5/32 to 7/32	C-1	0.500 ± 0.01	4 1/4	3/4	1/2	1/4	6 3/4	45
"	1/4	C-1	0.500 ± 0.01	4 1/4	1	1/2	1/2	6 3/4	45
"	5/16	C-1	0.500 ± 0.01	4 1/4	1 1/4	1/2	1/2	6 3/4	45
"	3/8	C-1	0.500 ± 0.01	4 1/4	1 1/2	1/2	1/2	6 3/4	45
Gas	Under 3/16	C-4	0.252 ± 0.005	2 1/2	3/8 min.	1/8		5	75
"	3/16 and over	C-1	0.500 ± 0.01	4 1/4	3/4 min.	1/4		6 3/4	75

Note: Test plate may be lengthened as desired to provide for more than one specimen.

Fig. 4—Test Plate for All-Weld-Metal Tension Specimen C-1 or C-4

chined from it. In the latter case, specimens *C*-2, *C*-3, *C*-4 or *C*-5 shall be used, choosing the specimen having the largest diameter which can be machined from the material to be tested. The portion of the specimen included in the gage length *B* shall consist entirely of metal from the deposited metal zone. All of these specimens are geometrically similar in all significant dimensions, therefore the properties determined from any one of them tend to be approximately the same as the properties determined from any other one. However, it is desirable that comparisons be made only between specimens of the same size.

In the event that filler metal is to be deposited specifically for the purpose of this test, test plates and specimens complying with the requirements of Fig. 4 shall be used. The apparatus, materials, methods and rate of depositing the weld metal in the test plate shall, so far as practicable, be the same as those used in making welds with the given filler metal.

NOTE: Due to unavoidable differences in the method of depositing the filler metal and in rates of cooling, the properties of the weld metal determined from a specimen will depend upon the dimensions of the adjacent metal.

For thermit welds a suitable refractory material shall be used for a trough in which the weld metal is to be allowed to solidify.

2. *Procedure.*—The diameter of the specimen at the middle of the reduced section shall be measured in inches and the gage length defined by a gage mark at each end. The specimen shall be ruptured under tensile load, and the maximum load in pounds shall be determined.

3. *Results.*—The tensile strength shall be obtained in pounds per sq. in., by dividing the maximum load by the cross-sectional area of the specimen at the middle. The cross-sectional area of the specimen shall be obtained by squaring the diameter of the specimen and multiplying by 0.785. The elongation shall be determined by removing the specimen from the machine, fitting the fractured ends of the specimen together, measuring the distance between the gage marks and subtracting the gage length. The per cent elongation shall be obtained by dividing the elongation by the gage length and multiplying by 100.

VII. Welded Butt Joints

General Statement: Individual specifications may designate which of the specimens described in this section shall be used, and the order in which they shall be cut from any prepared plate or pipe sample. No weld in a plate sample shall be begun or ended nearer than one inch to any portion of a welded specimen taken from that plate.

A. Soundness: Nick-Break Test

1. *Specimen.*—For a welded butt joint in plate, the nick-break specimen, *D*-1, shall comply with the requirements of Fig. 5.

For a welded butt joint in pipe or tubing the nick-break specimen, *D*-2, shall comply with the requirements of Fig. 6.

2. *Procedure.*—The specimen shall be supported substantially in accordance with Fig. 7 and ruptured by a force which, unless otherwise specified, may be applied either slowly or suddenly as by one or more blows of a hammer.

NOTE: A sharp sudden heavy blow is often specified. There appears to be but little evidence to indicate that there is any appreciable difference in the appearance of the fractured surface caused by a difference in the rate of applying the force.

3. *Results.*—The surfaces of the fracture shall be examined for soundness. (See Sec. III and Note, Sec. VI, *B* 3.)

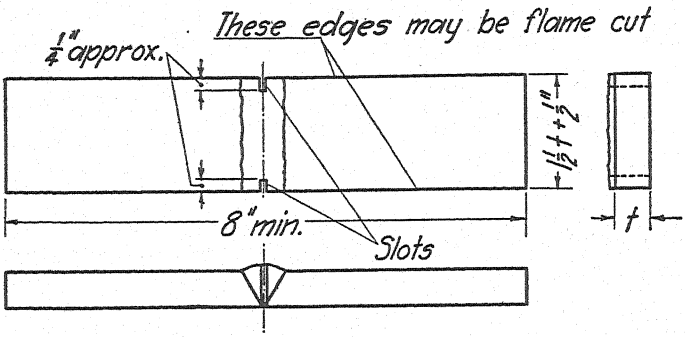


Fig. 5—Nick-Break Specimen *D*-1 (Plate)

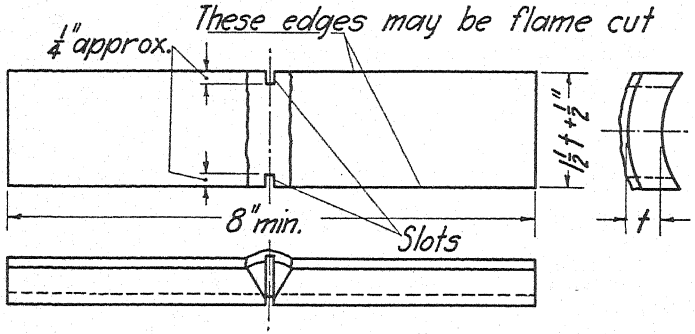


Fig. 6—Nick-Break Specimen *D*-2 (Pipe)

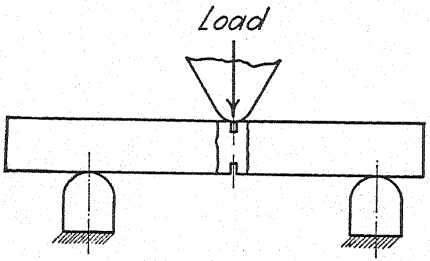
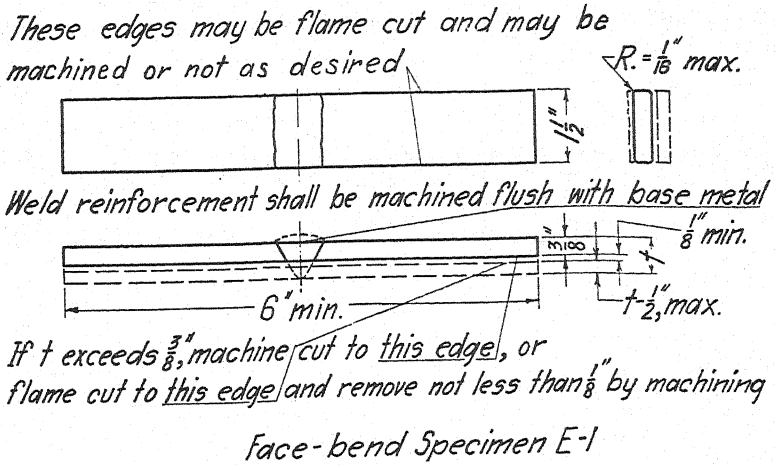


Fig. 7—Method of Rupturing Nick-Break Specimens

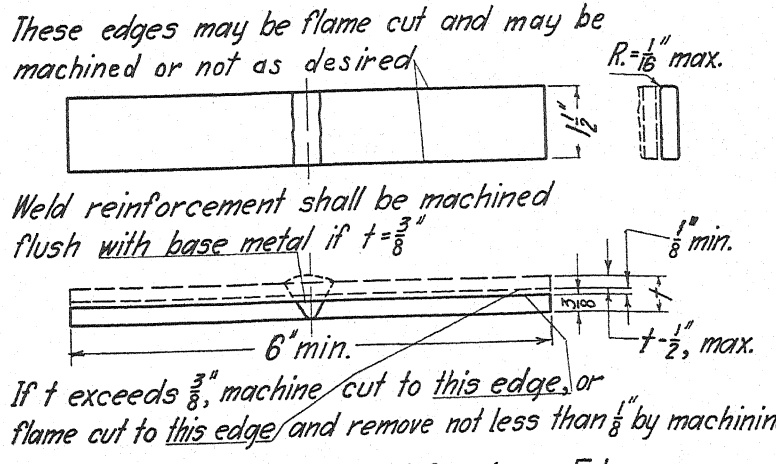
B. Soundness: Guided-Bend Test

1. *Specimens.*—For welded butt joints in plate, the face-bend specimen, *E*-1, and the root-bend specimen, *F*-1, shall comply with the requirements of Fig. 8.

For welded butt joints in pipe or tubing, the face-bend specimen, *E*-2, and the root-bend specimen, *F*-2, shall comply with the requirements of Fig. 9.



Face-bend Specimen E-1



Root-bend Specimen F-1

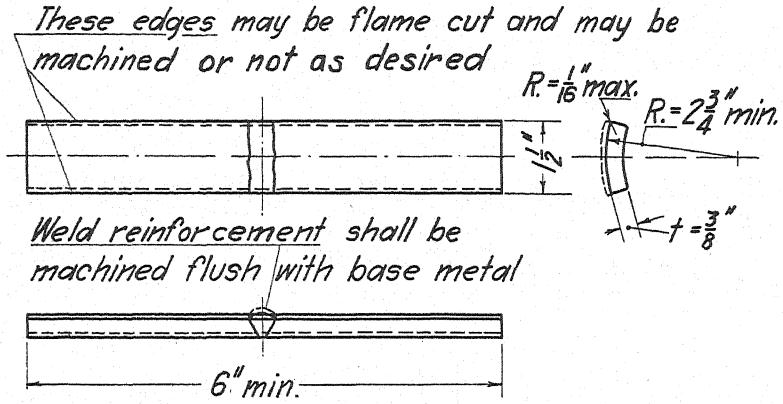
Note- the face bend and root bend tests are not applicable if the plate thickness (t) is less than 3/8"

Fig. 8—Face- and Root-Bend Specimens E-1 and F-1 (Plate)

The side-bend specimen, *G*, shall comply with the requirements of Fig. 10.

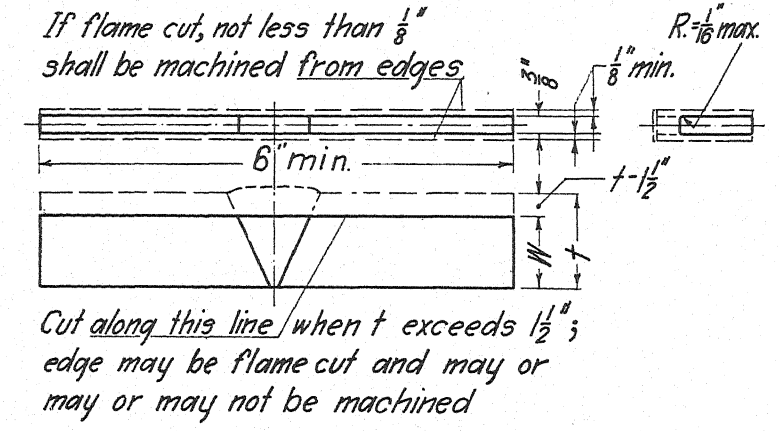
Tool marks, if any, shall be lengthwise of the specimen.

NOTE: Tests have shown that the severity of the guided-bend test increases to some extent with increasing width/thickness ratio of the



Note: This test as now specified is intended for pipe of 3/8-inch nominal wall thickness only, and is not considered suitable for pipe having a nominal diameter of less than 6 inches.

Fig. 9—Face- or Root-Bend Specimens, *E*-2 or *F*-2, Respectively (Pipe)



t, in.	W, in.
3/4" to 1 1/2"	t
> 1 1/2"	1 1/2"

Note: The side-bend test is not applicable if the plate thickness (t) is less than 3/4 inch.

Fig. 10—Side-Bend Specimen *G*

specimen. Results of the side-bend test are therefore not directly comparable when obtained on specimens *G*, Fig. 10, having different widths *W*.

2. *Procedure.*—Each specimen shall be bent in a jig having the working contour shown in Fig. 11, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving the plunger member with relation to the die member.

The specimen shall be placed on the die member of the jig with the weld at midspan. Face-bend specimens, *E*-1 and *E*-2, shall be placed with the face of the weld directed toward the gap; root-bend specimens, *F*-1 and *F*-2, shall be placed with the root of the weld directed toward the gap; side-bend specimen, *G*, shall be placed with that side showing the greater defects, if any, directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a $^{1}/_{32}$-in. diameter wire cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig.

3. *Results.*—The convex surface of the specimen shall be examined for the appearance of cracks or other open defects. Any specimen in which a crack or other open defect is present after the bending, exceeding a specified size measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered unless they exceed a similarly specified size.

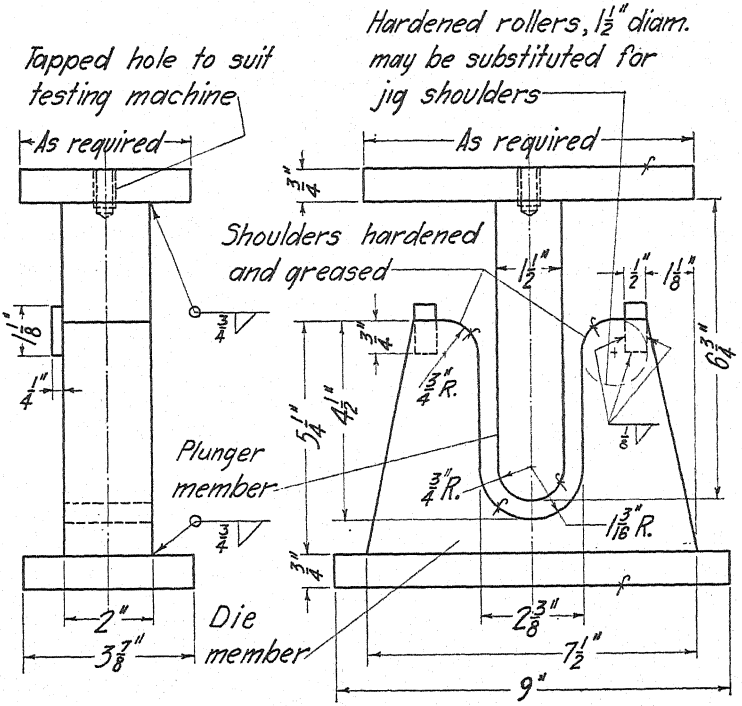


Fig. 11—Guided-Bend Test Jig

C. Tensile Strength

1. *Specimens.*—For a welded butt joint in plate, the tension specimen *H*-1 shall comply with the requirements of Fig. 12.

For a circumferentially-welded butt joint in pipe or tubing having a nominal diameter exceeding 2 inches, either specimen *H*-2 or *H*-3 may be used as called for in the code or specification. Specimen *H*-2 shall comply with the requirements of Fig. 13. The ends of the specimen may either be

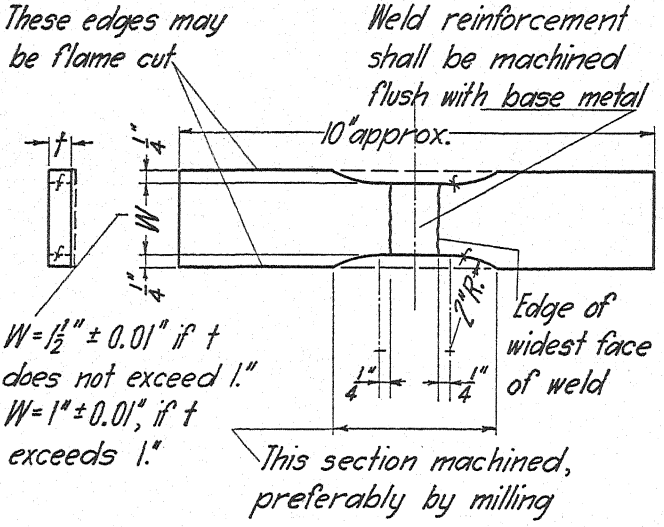


Fig. 12—Tension Specimen *H*-1 (Plate)

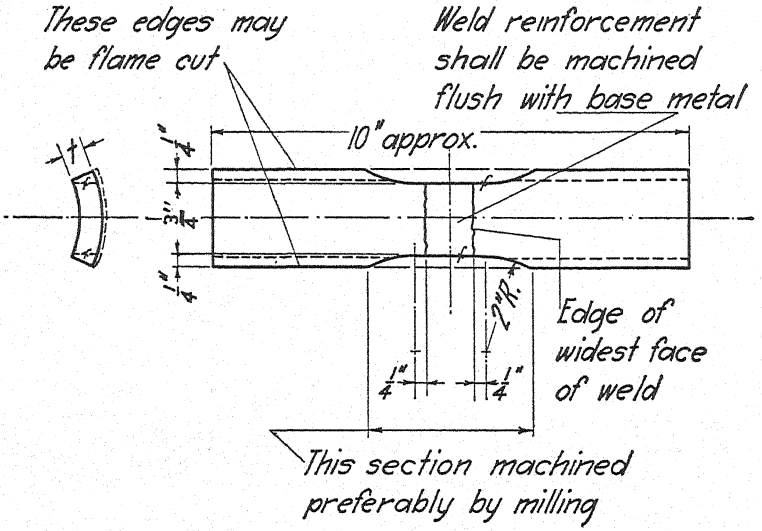


Fig. 13—Tension Specimen *H*-2 (Pipe)

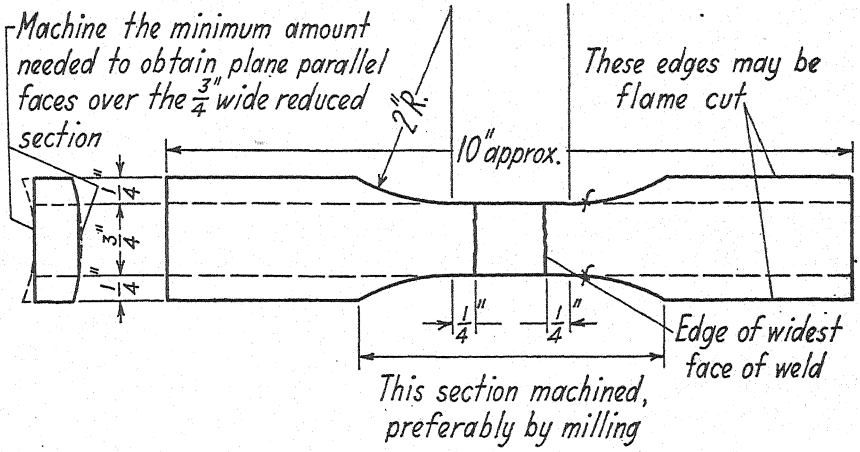


Fig. 14—Tension Specimen *H*-3 (Pipe)

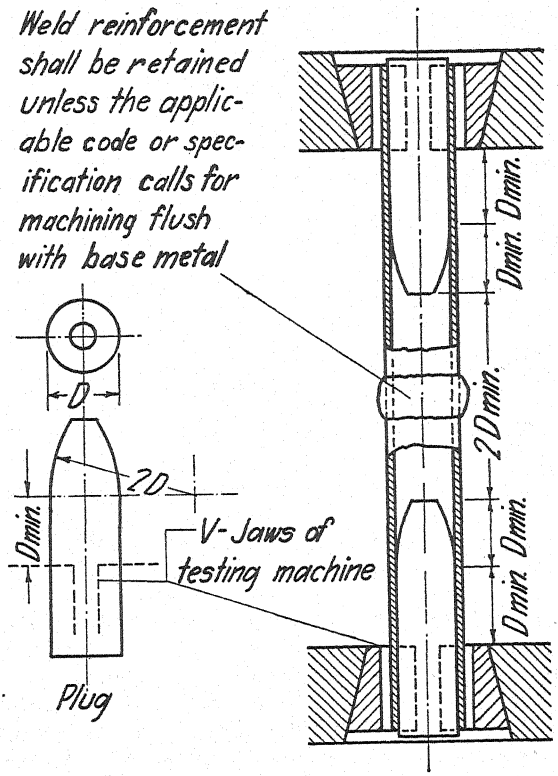


Fig. 15—Tension Specimen *H*-4 (Pipe)

flattened by any suitable means or the ends may be placed in the grips of the testing machine without flattening. Specimen *H*-3 shall comply with the requirements of Fig. 14. This specimen is not recommended for wall thicknesses less than $^3/_8$ inch nominal.

For circumferentially-welded butt joints in pipe or tubing having a nominal diameter not exceeding 2 inches, the specimen *H*-4 (full section specimen) shall comply with the requirements of Fig. 15.

2. *Procedure.*—For specimens *H*-1, *H*-2 and *H*-3, the least width and corresponding thickness of the reduced section shall be measured in inches. For specimen *H*-4, the average outside diameter, *O.D.*, of the base metal at a distance not exceeding $^1/_2$ inch from the boundary between the base metal and the weld metal, and also the average inside diameter, *I.D.*, of the base metal at either end of the specimen shall be measured in inches. The specimen shall be ruptured under tensile load and the maximum load in pounds shall be determined.

3. *Results.*—The cross-sectional area shall be obtained as follows:

Specimen	*Cross-Sectional Area* =
H-1, *H*-2 or *H*-3	width × thickness
H-4	$0.785\ (O.D.^2 - I.D.^2)$

The *tensile strength* in pounds per sq. in. shall be obtained by dividing the maximum load by the cross-sectional area.

D. Ductility: Free-Bend Test

1. *Specimen.*—For welded butt joints in plate, the specimen, *J*-1, shall comply with the requirements of Fig. 16.

For a circumferentially-welded butt joint in pipe or tubing, the specimen, *J*-2, shall comply with the requirements of Fig. 17.

In both cases the width shall be 1.5 multiplied by the thickness of the specimen. Each corner lengthwise of the specimen shall be rounded in a radius not exceeding $^1/_{10}$ the thickness (t) of the specimen. Tool marks, if any, shall be lengthwise of the specimen.

If the line between the weld metal and the base metal is not distinctly visible when the specimen is ready for testing, the surface of the specimen shall be etched with a suitable reagent.

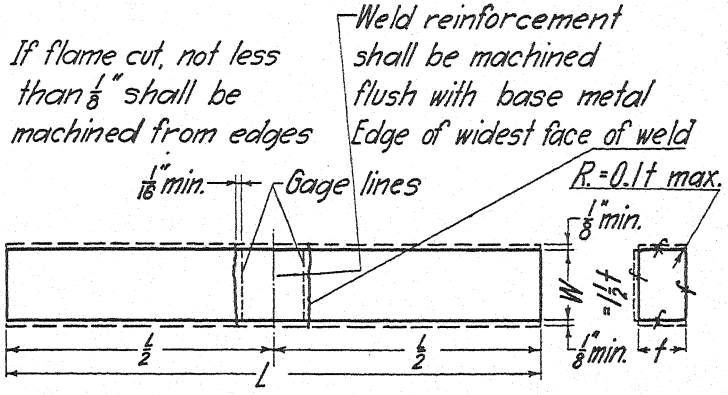
2. *Procedure.—Gage Lines:* The gage lines shall be lightly scribed on the face of the weld. The gage length (distance between gage lines) shall be approximately $^1/_8$ inch less than the width of the face of the weld, and shall be measured in inches to the nearest 0.01 inch.

For single groove welds, the gage lines shall be on the wider face of the weld.

For double groove welds, the gage lines on one-half the specimens shall be on one face of the weld, and on the other half of the specimens, on the other face.

Initial Bend: Each specimen shall be bent initially by the use of a device complying with the requirements of Fig. 18. The surface of the specimen containing the gage line shall be directed toward the supports. The weld shall be at midspan of both the supports and the loading block.

Alternate Initial Bend: If the purchaser and the vendor agree, the initial bend may be made by holding each specimen in the jaws of a vise with one-third the length of the specimen projecting from the jaws, then bending



Dimensions

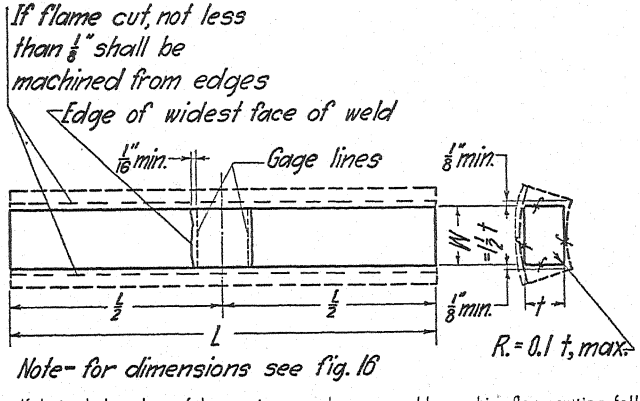
t, in.	1/4	3/8	1/2	5/8	3/4	1	1 1/4	1 1/2	2	2 1/2
W, in.	3/8	9/16	3/4	15/16	1 1/8	1 1/2	1 7/8	2 1/4	3	3 3/4
L min, in.	6	8	9	10	11	12	13 1/2	15	18	21
B* min., in.	1 1/4	1 1/4	1 1/4	2	2	2	2	2	2	3

*See fig. 18

Note:- the length L is suggestive only, not mandatory

Note: If desired, the edges of the specimen may be prepared by machine flame cutting, followed by rounding of the corners with a file, though this may be a more severe test.

Fig. 16—Free-Bend Specimen J-1 (Plate)



Note: If desired, the edges of the specimen may be prepared by machine flame cutting, followed by rounding of the corners with a file, though this may be a more severe test.

Fig. 17—Free-Bend Specimen J-2 (Pipe)

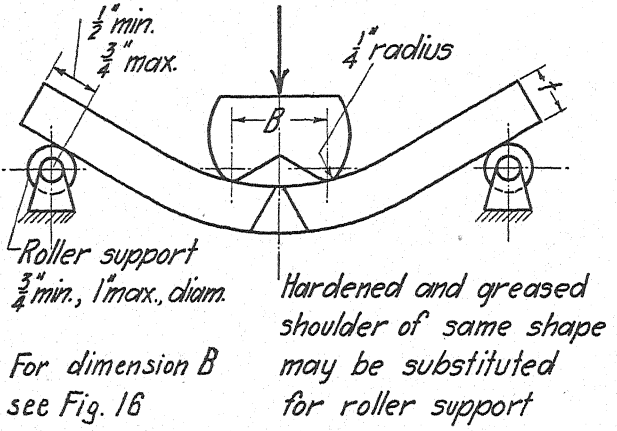


Fig. 18—Initial Bend for Free-Bend Specimens

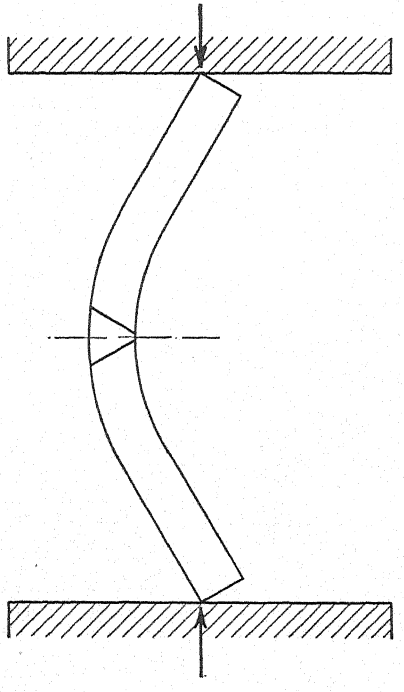


Fig. 19—Final Bend for Free-Bend Specimens

the specimen away from the gage lines through an angle of from 30 to 45° by blows of a hammer. The other end of the specimen shall be bent in the same way. In order that the final bend shall be centered on the weld, the initial bends shall be symmetrical with respect to the weld, and both ends shall be bent through the same angle. In cases of specimens having a thickness of $^1/_2$-in. or less, the initial bend may also be started at the weld by placing the specimen in the guided-bend test jig shown in Fig. 11.

Final Bend: Compressive forces shall be applied to the ends of the specimen, continuously decreasing the distance between the ends, substantially in accordance with Fig. 19. When either a crack or a depression exceeding a specified size in any direction appears on the convex face of the specimen, the load shall immediately be removed. If no crack appears, the specimen shall be bent double. Cracks occurring on the corners of the specimen during testing shall not be considered unless they exceed a similarly specified size.

NOTE: Any convenient means, such as a vise or a testing machine may be used for the final bend. The use of a device complying with Fig. 20 is recommended. It prevents the ends of the specimen from slipping as it is bent. Life and property may be endangered if the specimen slips.

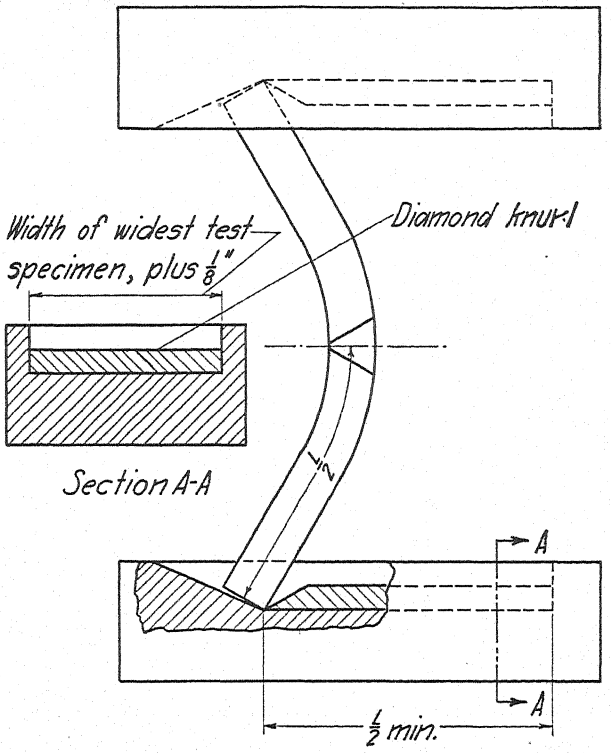


Fig. 20—Recommended Device for Final Bending of Free-Bend Specimens

3. *Results.*—The elongation shall be determined by measuring the minimum distance between the gage lines, along the convex surface of the weld, to the nearest 0.01 inch and subtracting the initial gage length. The per cent *elongation* shall be obtained by dividing the elongation by the initial gage length and multiplying by 100.

NOTE: A flexible steel scale graduated in hundredths of an inch and a magnifying glass may conveniently be used when determining the elongation.

VIII. Fillet-Welded Joints

A. Soundness: Fillet-Weld-Break Test

1. *Specimen.*—The fillet-weld-break specimen, *K*, shall comply with the requirements of Fig. 21.

2. *Procedure.*—A force, *A*, shall be applied to the specimen substantially in accordance with Fig. 22, until rupture of the specimen occurs. The force may be applied by any convenient means.

NOTE: A press, a testing machine or blows of a hammer may be used.

3. *Results.*—The surfaces of the fracture shall be examined for soundness. (See Sec. III and Note Sec. VI, *B* 3).

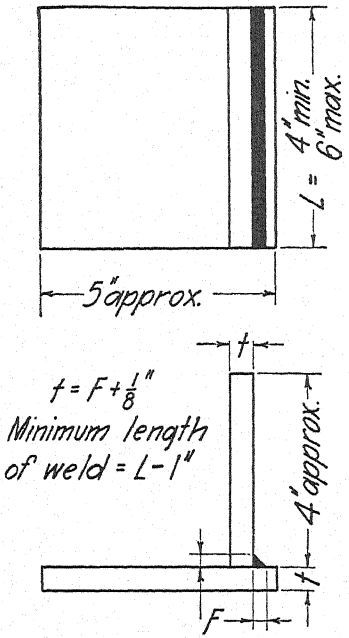


Fig. 21—Fillet-Weld-Break Specimen *K*

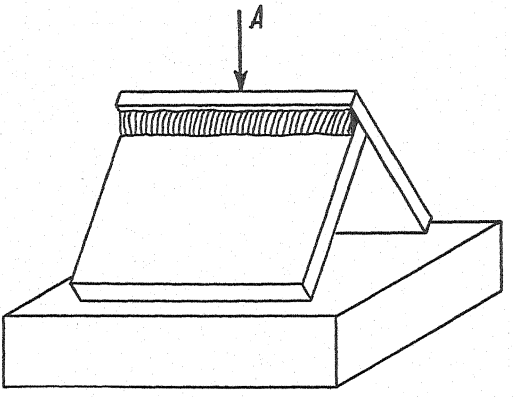


Fig. 22—Method of Rupturing Fillet-Weld-Break Specimen *K*

B. Shearing Strength: Transverse Welds

1. *Specimens.—Type A:* The transverse fillet-weld specimen, *L*-1, shall comply with the requirements given in Fig. 23. (For alternative method of preparing this specimen, see note under paragraph *C* 1.)

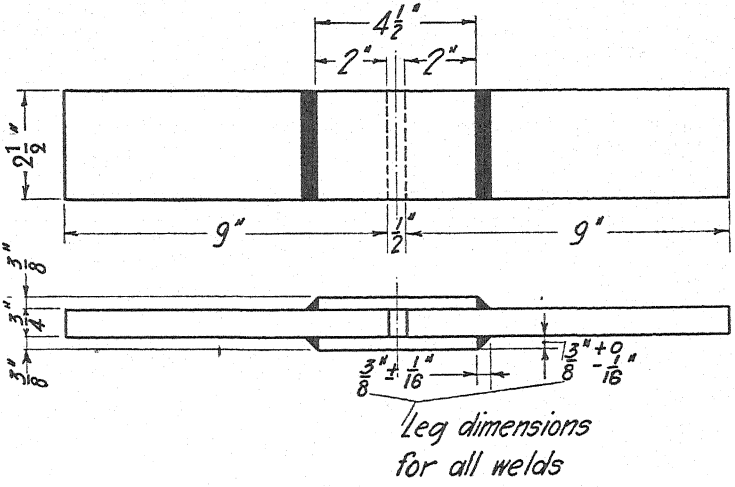


Fig. 23—Transverse Fillet-Weld Shearing Specimen *L*-1

Type B: The transverse fillet-weld specimen, *L*-2, shall comply with the requirements of Fig. 24. (For alternative method of preparing this specimen, see note under paragraph *C* 1.)

NOTE: These two types of specimen are currently used for shear tests of fillet welds; type *A*, where comparative rather than absolute value of strength per linear inch of fillet weld is sufficient, and where because of cost or of time limitations it is desired to avoid machining of specimens; and type *B*, where more nearly exact values are desired.

2. *Procedure.*—The width of the specimen shall be measured in inches. The specimen shall be ruptured under tensile load, and the maximum load in pounds shall be determined.

3. *Results.*—The shearing strength of the welds in pounds per linear inch shall be obtained by dividing the maximum force by twice the width of the specimen.

The shearing strength of the welds in pounds per square inch shall be obtained by dividing the shearing strength in pounds per linear inch by the average throat dimension of the welds in inches.

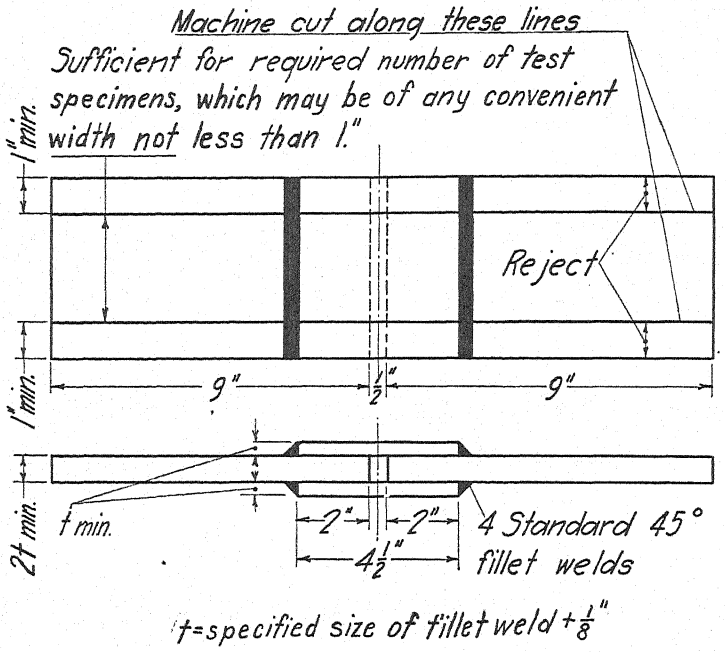


Fig. 24—Transverse Fillet-Weld Shearing Specimen *L*-2

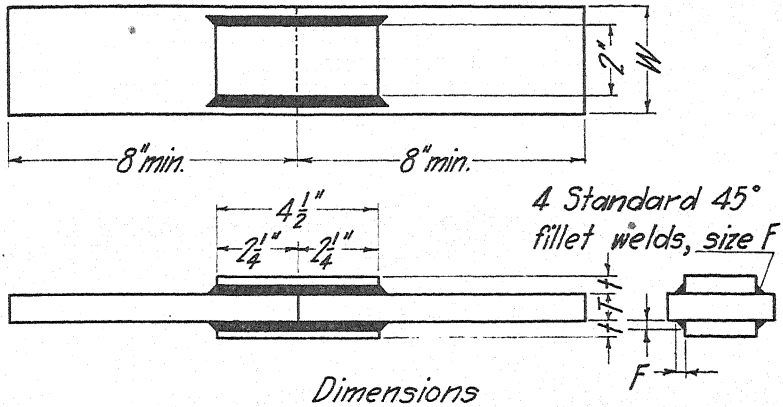
C. Shearing Strength: Longitudinal Welds

1. *Specimen.*—The longitudinal fillet-weld specimen, *M*, after welding shall comply with the requirements of Fig. 25 and after machining shall comply with the requirements of Fig. 26.

NOTE: For preparing specimens *L*-1, *L*-2, and *M* the following alternative method shall be permissible: Instead of depositing the fillet welds against a single center plate (center plate indicated by dimension "T" in Fig. 25), the welds may be deposited against plates of thickness $^1/_2$ T, where T is the thickness of the center plate, and the specimen prepared in two halves as shown in Fig. 27 (*a*). The two halves of the specimen shall then be placed back-to-back and united by means of an edge joint (made with a bead weld or a $^5/_{32}$-in. 90-degree single-V groove weld, deposited by the metal arc process), as shown in Fig. 27 (*b*).

2. *Procedure.*—The length of each weld shall be measured in inches. The specimen shall be ruptured under tensile load, and the maximum force in pounds shall be determined.

3. *Results.*—The *shearing strength* of the welds in pounds per linear inch shall be obtained by dividing the maximum force by the sum of the lengths of the welds which ruptured.



Dimensions

Size of weld F, in.	1/8	1/4	3/8	1/2
Thickness t, in., min.	3/8	1/2	3/4	1
Thickness T, in., min.	3/8	3/4	1	1 1/4
Width W, in.	3	3	3	3 1/2

Fig. 25—Longitudinal Fillet-Weld Shearing Specimen *M* After Welding

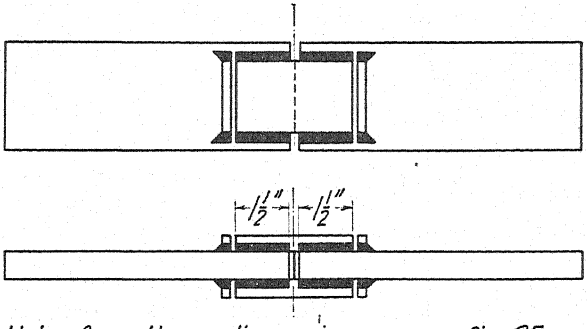


Fig. 26—Longitudinal Fillet-Weld Shearing Specimen *M* After Machining

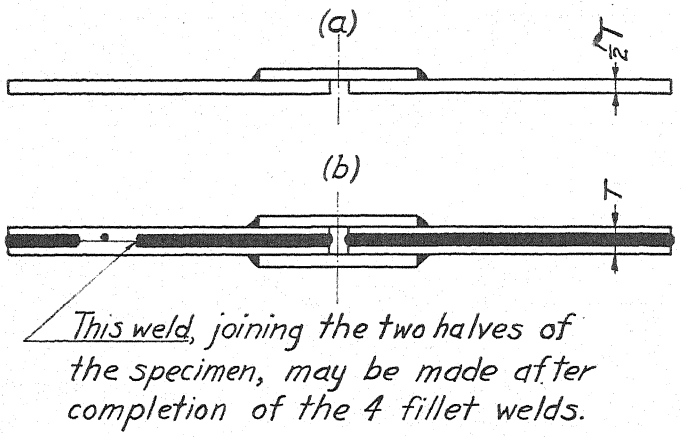


Fig. 27—Alternate Method of Preparing Fillet Weld Shearing Specimens (Specimen illustrated is transverse shearing specimen. For specific details and dimensions see Figs. 23, 24 and 25.)

APPENDIX A

SUGGESTED METHODS OF TESTING SPOT WELDS*

General

All spot-welding test fall, in general, into two groups:

1. Procedure qualification tests.
2. Material weldability tests.

The function of the first is primarily to show quantitatively the extent of fusion obtained by a specific procedure in a spot weld and also to some extent to indicate the quality of the metal in and around the weld, as compared to a predetermined standard. The function of the second is to establish the standards for structural performance of spot welds on specific metals and alloys under different service conditions.

It is assumed that all tests will be made with full laboratory facilities available. When tests have to be performed during manufacturing operation with shop facilities available the procedure qualification test only is recommended.

1. Procedure Qualification Test

This test shall consist of a lap shear test by pulling to destruction on a standard testing machine, a test specimen obtained by lapping two strips of metal and joining them by a single spot weld; it shall be supplemented by a visual examination test to determine the degree of penetration and the structure of the weld.

* Recommended by Resistance Welding Committee of the Industrial Division of the Welding Research Committee—The Engineering Foundation and modified by A. W. S. Resistance Welding Standards Committee.

The ultimate strength of the specimen, the diameter of the weld slug, the manner of failure whether by shear of the weld metal or by tear of the parent metal, and whether a ductile or brittle fracture shall be recorded.

The record of the specimen shall include complete description of the properties of the metal such as gage thickness, tensile strength, ductility and chemical composition.

The dimensions of the test specimens shall be as follows:

Metal Thickness	Width, Ferrous Metals and Alloys, Copper, Nickel and Copper-Nickel Alloys, In.	Minimum Length Each Piece, In.
Up to 0.030 in.	5/8	3
0.031 to 0.050 in.	1	4
0.051 to 0.100 in.	1 1/2	5
Above 0.100 in.	2 (min.)	6

The above dimensions are also recommended for aluminum and its alloys. However, where for reasons of economy it is desired to keep the widths of the specimens to absolute minimum, the following dimensions may be used.

Metal Thickness	Width, Aluminum and Its Alloys, In.	Minimum Length Each Piece, In.
Up to 0.030 in.	5/8	3
0.031 to 0.045 in.	3/4	4
0.046 to 0.059 in.	1	4
0.060 to 0.070 in.	1 1/4	5
0.071 to 0.100 in.	1 1/2	5
Above 0.100 in.	2	6

The amount of overlap is to be equal to the width of the specimen in all cases. The distance that each specimen is inserted in each grip is to be 2 in. in all cases.

The effect of eccentricity with the use of the above specimens can be disregarded. Whenever desired for reasons of economy, the use of shorter specimens can be allowed provided that proof is made that the effects of eccentricity, misalignment, stress concentration, etc., are not increased and that the results obtained are substantially the same as with the use of standard specimens.

Whenever feasible the length of specimens should be made in the direction of rolling.

The visual examination shall be conducted on a cross-sectioned and etched specimen with the cross-section taken through the center of the weld and with sufficient magnification to show both the weld penetration and the defects in the weld structure such as cracks, blowholes and porosity. The proper extent of weld penetration varies with different metals and members joined and must be established by proper lap shear tests and material weldability tests.

The projection weld shall be tested in the same fashion as the single spot welds, except that the group of projections welded simultaneously should be treated as a single spot weld as far as testing is concerned. Whenever impossible to pull the projection welds in shear, the etched test alone can be used, provided every projection weld is examined.

2. Material Weldability Test

The material weldability test shall consist of the standard lap shear test as described above, supplemented by additional tests as follows:

(*a*) *U-Shaped Tension Specimen.*—This test shall consist of pulling in tension to destruction on a standard testing machine a U-shaped specimen properly supported by spacer blocks and clamps and prepared as follows:

Two metal strips 2 x 6 in. with a $^{9}/_{16}$-in. hole near each end shall each be bent 90° at a distance of 2 in. from each end to form each a three-sided box or wide U. The specimens shall then be placed back to back with their sides carefully lined up to lie in the same respective planes and jointed together by means of a single spot weld in the center of the adjoining bottoms. Two flat-faced square fixtures shall be used to fit snugly into each U and preserve its shape during the test. A $^{1}/_{2}$-in. through bolt shall be used to hold the specimens to the fixtures. The radius of bend of the corners of the fixtures, fitting into the bend of the U, shall not be less than $^{1}/_{4}$ in.

The fixture shall be supported in the grips of the testing machine in such manner as to ensure good alignment of the weld.

The ultimate strength of the weld, the diameter of the weld slug and the method of fracture shall be recorded.

The ratio of the U specimen tension strength to the shear pull strength for spots of the same diameter shall be considered as the measure of ductility of the spot weld made on the material under consideration.

(*b*) *Fatigue Tests.*—Proper methods of testing spot welds in fatigue are still under investigation and will be recommended later.

3. Approximate or Rough Shop Tests

The tests described above establish quantitatively certain essential properties of spot welds. It is sometimes desirable before conducting these exact tests to determine with the least possible effort and in a very general way the extent of fusion present in a spot weld made under certain conditions. In such cases certain simplified and approximate tests requiring considerably less time and equipment can be used, such as twist or torsion and peel tests. It must be remembered, however, that these rough tests are in no way a substitute, or even an approximation of the tests recommended above, as they in no way convey any quantitative information but simply show whether or not any fusion has taken place.

(*a*) *The Twist or Torsion Test.*—This test consists of holding one welded member edgewise in a vise and rotating the other member also edgewise around the spot weld as an axis and in the plane of the joined surfaces. In this manner the bond between the two members can be severed with comparatively little effort and an indication of its efficiency obtained from the angle of twist necessary to effect the severance. A certain indication of the ductility of the weld metal can also be obtained from the extent of the angle of twist, provided the failure occurs in the weld metal and not in the parent metal around the periphery of the weld.

(*b*) *Peel or Pull-Out Test.*—This test consists of prying apart the joined surfaces by either bending them back onto themselves and peeling out the

weld metal, or by inserting a chisel between the surfaces and close to the weld. In either case failure of the parent metal around the periphery of the weld is indication of extensive fusion in the weld.

The twist and peel tests provide a useful rough and ready check on the spot weld. However, it is not recommended for anything except a means of determining whether any fusion or welding has taken place at all.

CHAPTER 33B

NON-DESTRUCTIVE EXAMINATION OF WELDS*

Visual Inspection. Magnetic Powder Method. Field Radiography: Code Requirements, X-Ray Equipment, X-Ray Technique, Test Block.

VISUAL INSPECTION OF METAL ARC WELDING

General

INSPECTION, as the term implies, involves the examination of an object by some method to determine whether that object fulfills certain requirements which may be definitely specified or are generally recognized as desirable. The method of inspection followed will vary depending upon the object to be inspected and the requirements to be met.

Visual inspection of any weld should not be made until the weld has been thoroughly cleaned of all scale and dirt. Care should be used in the cleaning operation such that the metal surface is not deformed so as to obscure surface indications of defects. The primary object of visual inspection is the detection of surface defects in the weld and the determination as to whether the welded joint is satisfactory as judged by established standards. It is necessary to inspect the material surfaces adjacent to and in the vicinity of the weld for cracks and for evidence of laminations, blisters or segregations which may have opened up due to welding. Usually the weld defects found by visual inspection can be successfully repaired by removal and rewelding without scrapping the welded object.

Adequate visual inspection requires suitable lighting facilities. A pocket flashlight and a low power magnifying glass will be found very helpful in detecting defects which might be missed otherwise. For structures not too large, proper positioning makes inspection easier and better. If there are portions of the structure to be inspected which will be inaccessible after completion, these portions should be inspected before the structure is completed.

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* Prepared by a committee consisting of H. H. Lester, Watertown Arsenal, *Chairman;* O. T. Barnett, Metal & Thermit Corp.; A. V. deForest, Massachusetts Institute of Technology; W. L. Warner, Watertown Arsenal.

Steel Castings

The inspection of castings repaired by welding is concerned with not only the surface defects which may occur in the welds, but also with the question of whether the original defect which necessitated the repair has been completely removed. The latter condition can best be determined by visual or magnetic powder examination after the defective area has been removed, and before welding. This examination should be required whenever the defective area is of any appreciable size or depth.

When the inspector cannot be present to observe the progress of the repair work and must base his acceptance of the finished job upon the final appearance of the repair welds, unless he is able to depend upon the integrity of the personnel engaged in the repair work, he may insist upon examination by radiographic methods. This requirement is, of course, dependent upon the nature and extent of the repairs required and the type of casting being repaired.

Weldments

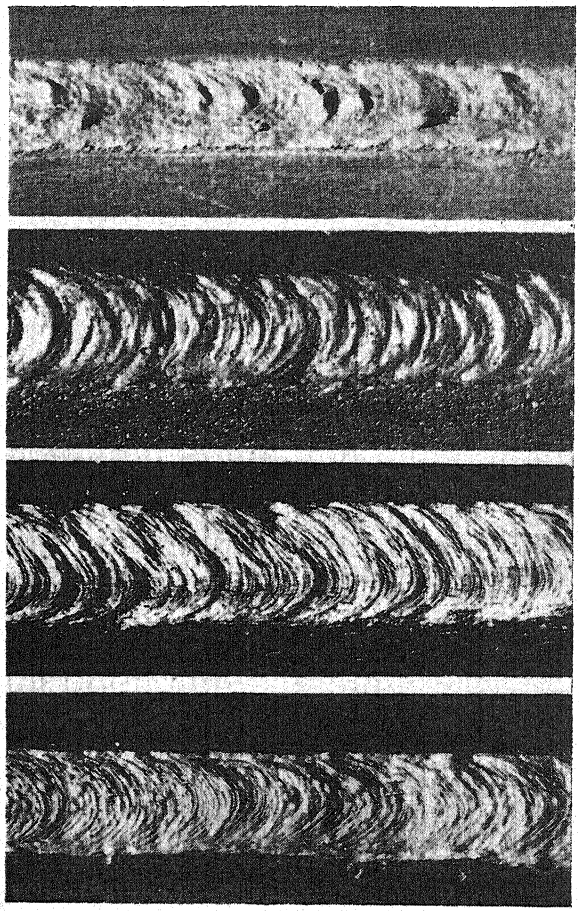
The dependability of any welded structure or weldment in service is obviously related to the character of the welds which hold the various parts of the structure together. Therefore, adequate weld inspection is of paramount importance.

Visual Inspection of the Weld

The surface of a good weld made in the flat position, with either bare or covered electrode, by an experienced welding operator will be uniform in width and contour as shown in Fig. 1. The surface of the weld made with the covered electrode is bright and shiny after the slag has been removed; whereas, the bare electrode weld presents a dull appearance due to a thin layer of iron oxide covering the weld metal surface. The ripples in the surface of the weld metal deposited by a bare electrode are more prominent and non-uniform than those of the covered electrode weld metal. To some extent the uniformity of these ripples is an indication of the steadiness of the operator's arm and his skill in holding a uniform arc and rate of travel. Also, the shape of the ripples is indicative of the position in which the weld was made.

The appearance of slag pockets, or "pock marks" as they are sometimes called, indicates that the slag formed by the electrode coating on the surface of the molten weld metal did not come entirely free from the melt on solidification of the metal. These pockets are formed because of improper welding conditions, i.e., the welding current was too low or the arc too short for the particular job or the rate of arc travel was too high or the combination of electrode and plate metal was unsatisfactory. This condition occurs most frequently with heavy, mineral type coatings but may occur with other types of coatings. Because of the nature of the formation of these cavities, they most often extend only through the layer of weld metal in which they are found. They should be chipped or ground out before the next layer of weld metal is applied, particularly on work which is to be radiographed.

The surface of the bare electrode fillet weld is usually quite convex; whereas, the surface of the covered electrode fillet weld is either only moderately convex or flat, or concave. These contours are illustrated by Fig. 2. Although contour No. 3 is not generally obtained with bare electrode contours, Nos. 3 and 7 are normal for single-pass fillets made with covered electrodes of the "all position, soft arc" type (A.W.S./A.S.T.M. Class E6012) in the flat position. These contours may also be obtained on multiple-pass fillet welds in the flat position by oscillating or weaving the arc using an electrode of the "down-hand" type (A.W.S./A.S.T.M. Class E6020). Contour No. 4 represents what may be obtained in a single-pass fillet weld made in the flat position with an electrode of the "down-hand" type. Quite often the contour obtained in the flat position with this type of electrode is a combination of Nos. 3 and 4.



Covered Electrode Fillet (Flat) Showing Pock Marks

Bare Electrode Fillet (Flat)

Covered Electrode Fillet (Horizontal)

Covered Electrode Fillet (Flat)

Fig. 1—Fillet Weld Surface

The contour of a flat fillet weld made with a covered electrode of the "all position, harsh arc" type (A.W.S./A.S.T.M. Class E6010) is usually similar to No. 7, although in some cases it may approximate No. 2 particularly in small, single-pass fillets in the flat position.

The size of a fillet weld is defined by accepted welding standards as the length of the leg of the largest isosceles right triangle which may be inscribed in the fillet cross-section. This is represented by the triangle *OMN* in Fig. 2, in which the length of either *OM* or *ON* in inches is the fillet size. Compliance of this dimension with that specified as a minimum

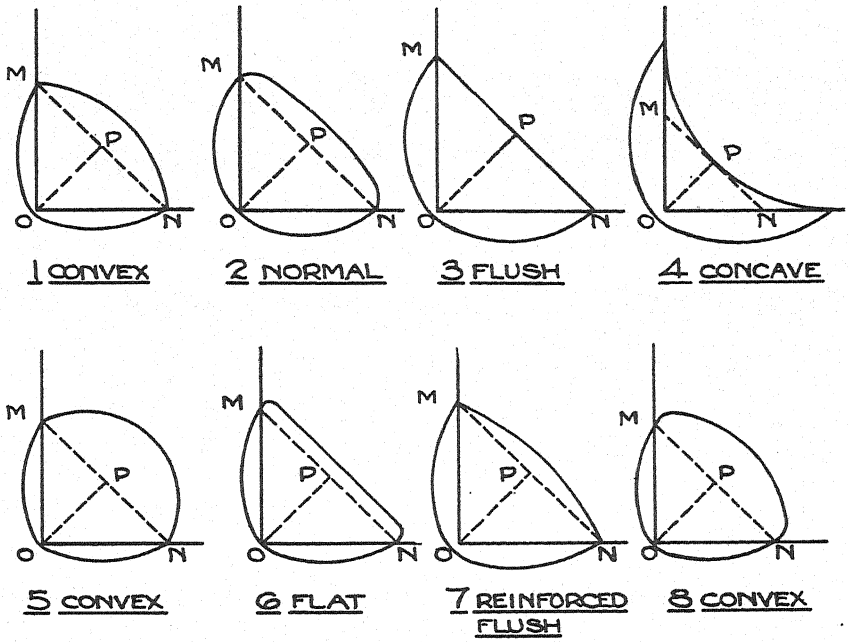


Fig. 2—Fillet Weld Contour

Desirable Fillet Contours
Bare Electrode—Nos. 2, 3 or 7
Covered Electrode—Nos. 3, 4 or 7

is determined by the use of a surface gage in a manner similar to that shown by Fig. 3. Ordinarily the size gage provides for an oversize tolerance of $^1/_{16}$ in. so that the size of fillet being measured in Fig. 3 is required to be at least $^5/_{16}$ in. (min.) and should not be over $^3/_8$ in. (max.) to comply with the $^5/_{16}$-in. gage illustrated. In this connection, it should be emphasized that rejection of oversized fillets is not always in order because, if the minimum size specified by the drawings or specifications is obtained, the requirements of the design are met. However, the presence of fillet welds which are considerably larger than the size specified may indicate that the operator has built up the deposit of weld metal to conceal some weld defect. It is very desirable that the inspector make an examination

of such welds from time to time, either by radiographic methods or by cutting a section out of the weld to examine the cross-section. The latter procedure should be used only as a last resort because patching of the hole from which the section was cut is usually necessary and often quite difficult.

When inspecting welds for surface defects, such as undercuts, cracks, excessive reinforcement, gas-holes, slag pockets, lack of fusion, size and general appearance, the inspector should keep clearly in mind a picture of the qualification test welds as a standard to follow for acceptance. Excessive reinforcement or convexity of fillet welds should be distinguished from oversize fillets because in the former case there is apt to be a lack of fusion in evidence, while in the latter case probably none.

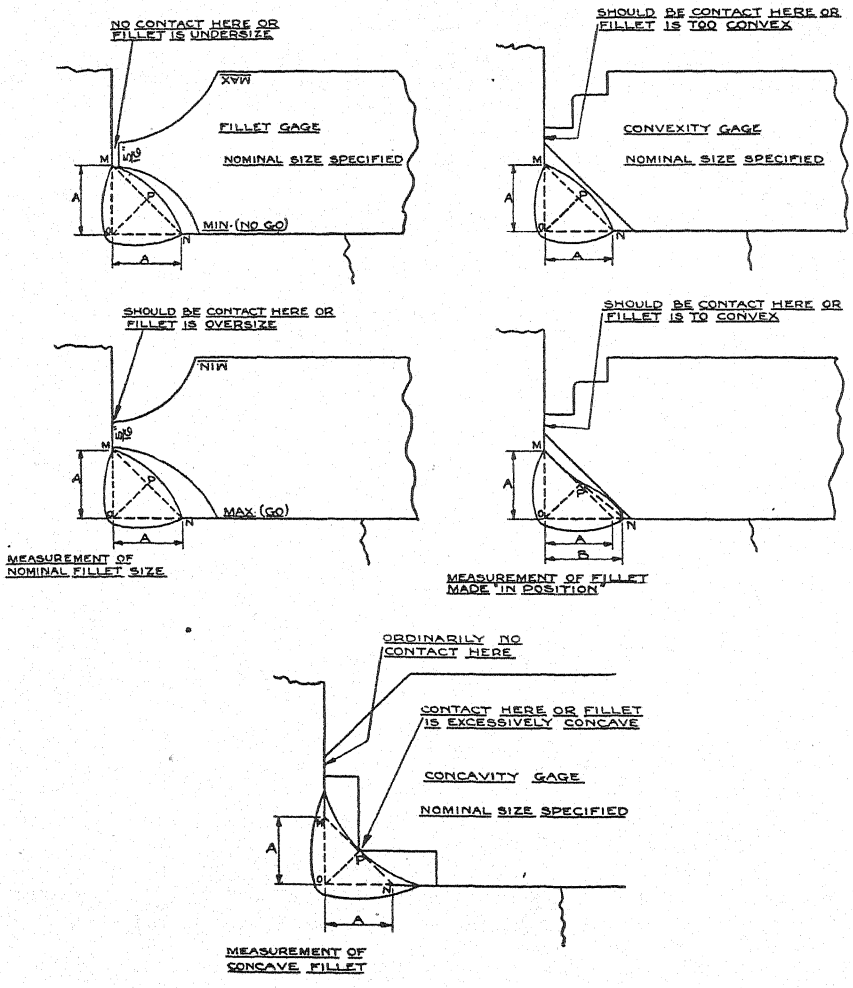


Fig. 3—Use of Fillet Weld Gage

In Fig. 4 is illustrated one form of surface evidence of lack of fusion at the edge of the weld. This same condition is exhibited differently by Fig. 5. In the right-hand photo of Fig. 5 the operator has endeavored to cover up the irregularities of the weld metal and the evidence of unfused areas by heavily peening the weld. Such practices should never be permitted because they are unnecessary when the operators are properly trained and the welding conditions are satisfactory. However the peening of heavy butt welds to relieve welding strains is permissible.

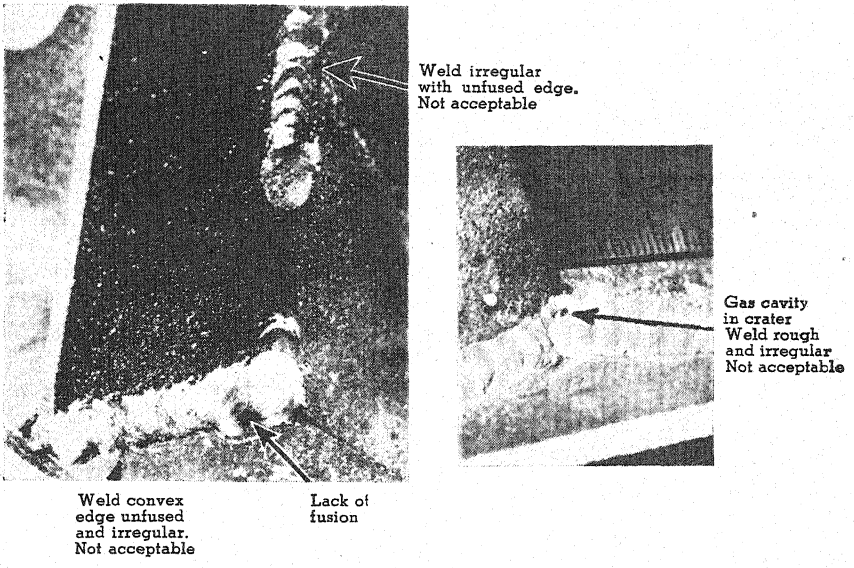


Fig. 4—Gas Cavities and Weld Irregularities

In the right hand photo of Fig. 4 is shown a gas-hole in the crater at the end of a weld. Such holes are distinguishable from slag pockets by the observation that they do not contain slag, are round in shape and do not conform to the ripple arrangement in the weld surface (see Fig. 1). They indicate the formation of gas in the melt which is not fully liberated before solidification. This condition may indicate improper welding procedure but, if generally prevalent throughout the weld, possibly the combination of electrode and plate is not compatible. It should not be allowed to continue.

Undercutting, as illustrated by Fig. 6, is generally due to faulty manipulations of the welding arc. A.W.S./A.S.T.M. Grades E6010 and E7010 electrodes undercut more readily than other types, and welds made in the vertical position are most subject to undercutting. An undercut reduces the net section of the part welded by the amount of the undercut, and is also a potential starting point for fatigue cracks under dynamic loading. The undercut may also mask a crack, a condition which is always difficult to determine. Undercuts should not be accepted.

Visual inspection of a butt-welded joint for penetration of the joint can be satisfactorily made where the joint is welded from only one side of the plate, and the back of the joint is accessible. If a seal bead or backing bead is used, then reliance must be placed on radiographic methods. On single-layer fillets, fairly accurate evidence regarding penetration can be obtained by examination of the depth and area of the crater at the end of the weld. Where the craters are filled during welding, this procedure is not effective.

The usual locations of cracks formed in and adjacent to the weld are indicated by Fig. 7. Cracks in the weld metal may occur longitudinally,

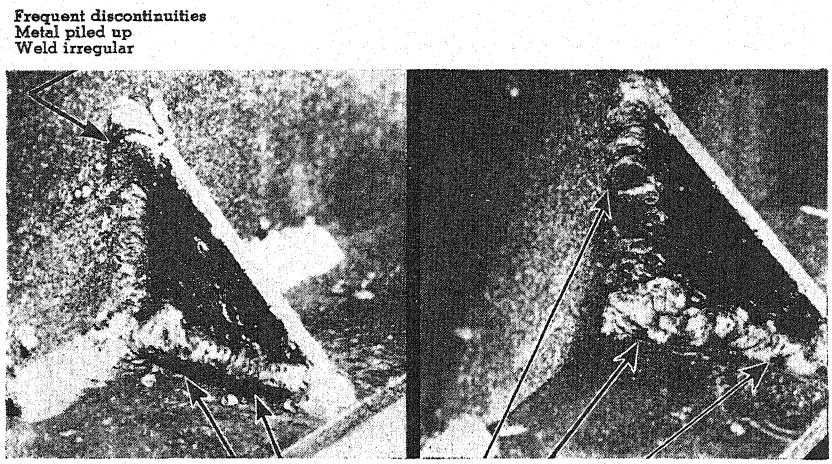


Fig. 5—Weld Irregularities

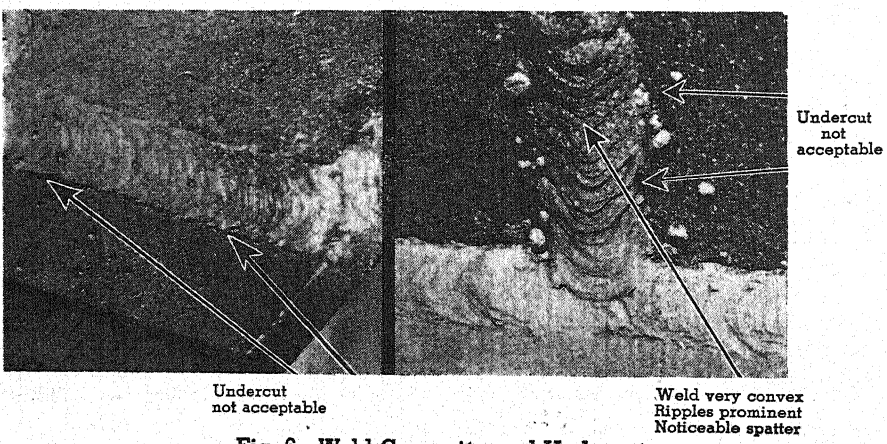


Fig. 6—Weld Convexity and Undercut

either along the center line of the weld, near the edges or both. The craters at the ends of weld runs may show longitudinal, transverse or star cracks. Transverse cracks in low carbon weld metal are rare.

Cracks in the plate occur more often in connection with fillet-welded joints than with butt-welded joints, mainly because of the physical differences with respect to the relative positions of weld metal and plate metal, and the directions of stress set up by the heating and cooling cycle. Plate cracks at the edge of either butt or fillet welds may extend into the plate for some distance from the weld, as shown by Fig. 8. The inspector must not only detect the cracks, but also determine the extent of them. For this purpose the magnifying glass and magnetic powder method will be found very desirable. All cracks should be ground, chipped or melted out and rewelded.

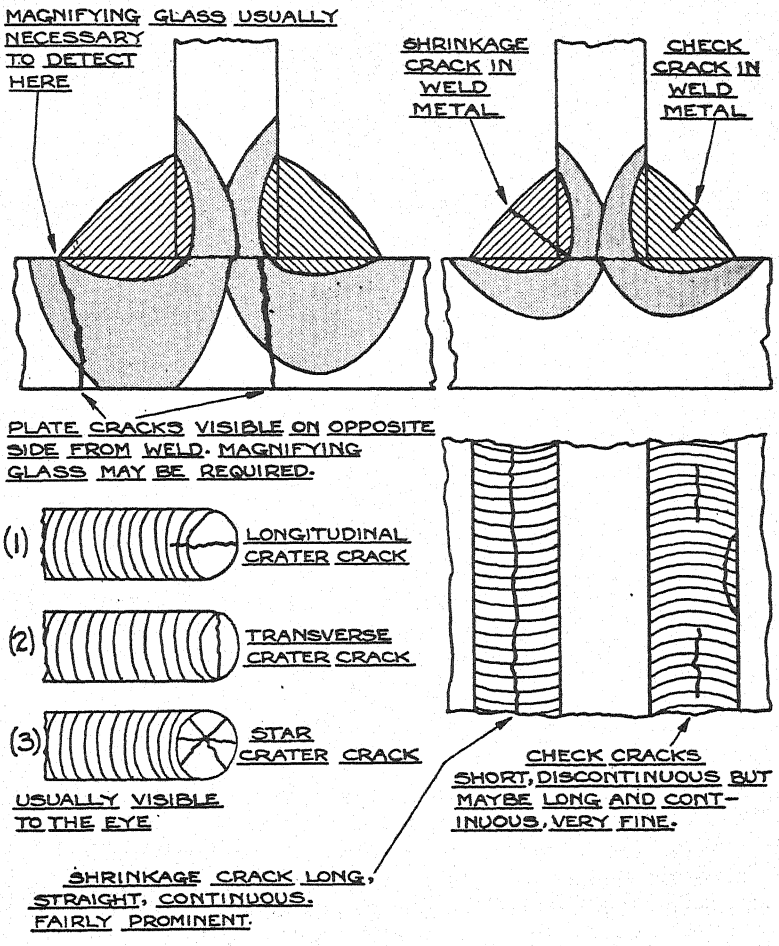


Fig. 7—Types of Weld and Plate Cracks

Repairs

It is essential that defects to be repaired be clearly marked so that the repair gang will know what and where they are. The marking should be legible and permanent enough that it will not be rubbed off in handling the weldment.

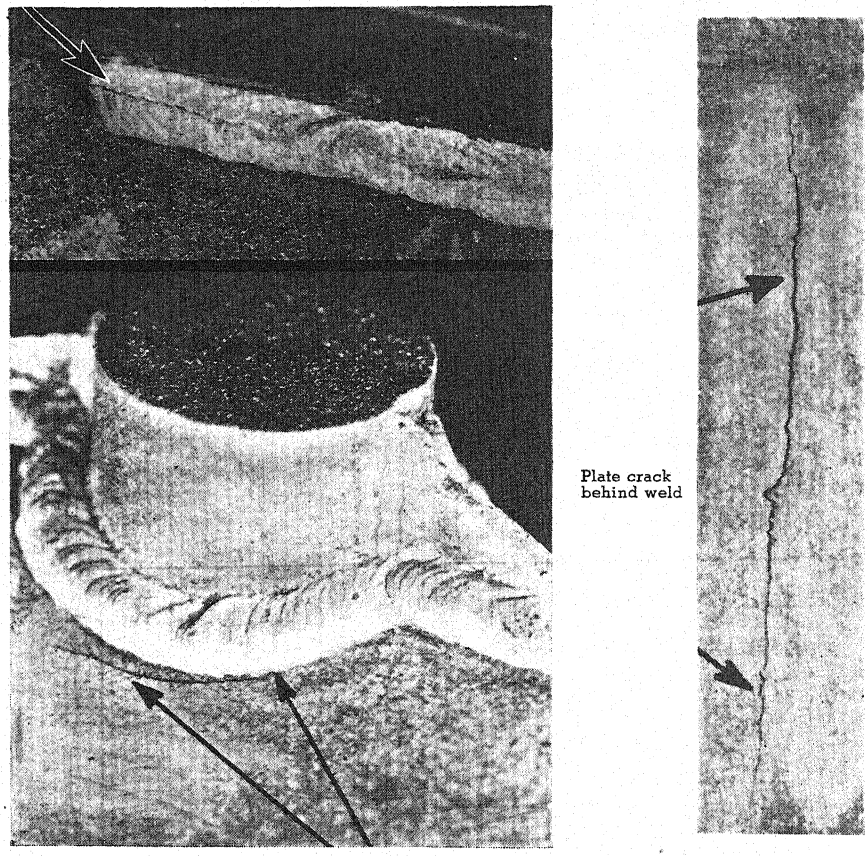


Fig. 8—Weld and Plate Cracks

The inspector should reinspect all repairs after they have been completed in order to insure that all designated repairs have been taken care of, and that rejectable defects are not present in the repair welds.

The inspector should insist that all cracks be removed before repair. This same requirement should also apply to undercuts, except very shallow ones, slag pockets and gas-holes. All weld repairing should be done prior to final heat treatment. Sometimes it is desirable to reinspect the welds

after heat treatment in order to insure against the acceptance of cracks which may have been caused by the heat-treatment operation.

Records

It is always desirable that records be kept of the operators who did the welding, whether it be repair of castings or fabrication of weldments. If adequate weld inspection records are kept of each repaired casting or weldment, and the operator or operators who did the welding, it will be found eventually that the operators develop a job consciousness and themselves become inspectors of a sort so that they inspect their own welds carefully before releasing the weldment or casting for final inspection. This is one of the benefits of a thorough, impartial inspection procedure, and the keeping of adequate records.

MAGNETIC POWDER METHOD

Magnetic powder tests are used to locate structural discontinuities in iron and steels except austenitic steels. These tests are not applicable to most non-ferrous metals or their alloys. Structural discontinuities may be cracks, slag inclusions, regions of imperfect fusion or incomplete penetration in welds. The method is particularly useful for the location of surface discontinuities, but may also indicate more deep-seated defects provided the magnetizing force is sufficient to produce a leakage field at the surface of the material.

The underlying principle of the magnetic powder test is relatively simple It may be stated as follows:

> If a magnetic flux be induced in a piece of ferro-magnetic material any abrupt discontinuity in its path results in a local flux leakage field, and if finely divided particles of ferro-magnetic material are brought into the vicinity, they offer a low reluctance path to the leakage field and take a position that tends to outline its effective boundaries.

It is to be noted that a necessary requirement is an "abrupt change in permeability." For instance, a narrow crack-like defect such as is occasionally found in welded joints causes a very abrupt change in permeability and is therefore of a type favorable for detection. The indications with rounded defects, such as blow-holes in castings, porosity in welds and wide, shallow surface seams do not give such "abrupt changes in permeability" and, therefore, are not defects of types favorable for detection.

The leakage field diffuses and decreases in intensity with increases in distance from its point of origin, hence the nearer the magnetic powder can be brought to the defect, the more positive the resulting pattern. For subsurface cracks, detectability depends upon a number of variables such as:

(*a*) Strength of magnetizing field.
(*b*) Distance of the defect from the surface.
(*c*) The ratio of the height of the defect to the thickness of section in which it is located.
(*d*) The width of the defect.

Because of the numerous variables involved, and other difficulties that might be encountered,* the accurate estimation of the depth of a crack below the surface as judged from the appearance of the pattern is very difficult. However, it is usually possible to state whether the defect is on the surface or beneath it from observation of the width of the pattern. Subsurface defects, when detectable, cause the formation of patterns which are broader and more diffused than the patterns caused by surface defects.

In order to produce the most desirable type of magnetization for the detection of defects in welds, the magnetizing current should be passed parallel to the longitudinal axis of the weld or the magnetic field should be at right angles to this axis. Steels having a relatively low retentivity, such as mild or low carbon steels, must be inspected while the magnetizing force is being applied, because the residual field is usually too weak for satisfactory indications.

Magnetizing Field

The most desirable type of a magnetizing field would be one confined entirely within the part and where there would be no external polarity or leakage field except at a defect. Such a condition, of course, is not obtainable either in practice or in theory, but the nearest approach to it is a field which is generated within the part itself and not by means of an external magnetizing force. This type of field can be induced by passing current of the required density† through the part to be inspected or through a central conductor and is called "Circular Magnetization." The next most effective magnetic field for magnetic powder inspection is a field generated within the part itself by means of an external winding or solenoid. Such a field induced in a part results in opposite polarity at each end of the part, and this type is generally called "Longitudinal Magnetization." A third method is to bring the part into the influence of an external magnetic field produced by permanent or electromagnets with iron cores. These may be single magnets or may be in the form of a yoke furnishing a complete iron path for flux travel. This method is in most cases the least satisfactory of the three, due to the introducing of powerful external poles with corresponding undesirable local poles in the part under inspection.

The magnetizing current may be either alternating current, direct current or rectified alternating current. A discussion of voltage, amperage, ampere turns and flux density requirements is not within the scope of this Chapter, and some experience is needed in selecting the proper type for a given location. When surface defects only are to be detected, alternating current is advantageous due to the pronounced skin effect. Skin effect is the tendency of alternating current to flow along the surface of a conductor and is a function of frequency. Where subsurface defects are important,

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* Rippled surface of the weld has a tendency at some points to hold mechanically the powder which might in some cases make determinations of patterns more difficult. However, if the surface is smooth, many indications would stand out clearly that otherwise might not be evident particularly to an untrained investigator.

† "The required current in some cases may be 300 or 400 amp.; in special cases higher currents are needed. For all practical purposes any surface that will attract or hold a tenpenny nail shows that the magnetizing force is sufficient. If the magnetizing force is such as to cause the powder to stand up like bristles on a brush, it is an indication that too much current is being used. At no time should the magnetizing force be so strong that the powder is not free to move at locations where no defects exist."

direct current is more effective than alternating current and is customarily used on welds, particularly in heavy materials. The current ripple which is characteristic of rectified alternating current seems to be frequently advantageous in increasing the mobility of the ferro-magnetic powder, and is often considered preferable for this reason.

Ferro-Magnetic Material

The nature of the magnetic powder used to obtain indications in these tests is a matter of importance. Because findings depend on interpretation of a powder pattern, it is desirable that the powder used be of uniform quality throughout any particular field or branch of industry. There are two methods of applying the finely divided magnetic powder, one called the "Dry Method" and the other the "Wet Method." With the dry method, as its name indicates, the powder is applied by various methods including sifting from hand shakers, vibrating screens, blowing on with a stream of air, dusting from a fine mesh cloth bag, or with small parts, simply rolling them in a quantity of powder. It is desirable that each individual particle of the powder have as high an effective permeability as practical and this is conditioned by two factors: first, the analysis of the particle and, second, its physical shape. The powder may be recovered and used over until it has become diluted with dirt and foreign non-magnetic particles. The dry method of inspection is customary for weld inspection and is more sensitive than the wet method for deep-seated defects.

Wet Method

In the wet method a very fine suspension of powder is maintained in an oil bath and the part to be inspected is dipped in this bath or the bath liquid may be flowed, brushed or sprayed on the part. This may be done while the part is under the influence of an internally generated magnetic field or where the residual magnetism in the part is relied on for the indication. The requirements for indicating material for the wet method are: first, it should have a high magnetic permeability; second, it should be in a form which may be readily mixed with the oil bath to be used without flocculation; third, the ratio of volume to mass of the individual particle be relatively large so that it will readily remain in suspension. The bath or oil used for maintaining this suspension should be colorless, should have a high flash and have as little odor as possible and should not be irritating to the skin. There are a number of light refined oils on the market which best fill these requirements. Kerosene is satisfactory if not irritating to the skin. The bath may be agitated by means of a motor-driven propeller or compressed air or by a motor-driven pump.

Occasionally the wet bath is followed by a rinse bath of a light volatile solvent which frees the part of all material except that adhering to the defect and evaporates rapidly, leaving a clean dry surface. The wet method is primarily used on finished parts and forging steels where nonmetallic stringers and very slight discontinuities are particularly important.

Demagnetization

Demagnetization after inspection is necessary and important in a number of applications. Demagnetization is commonly routine practice in the

aircraft field, and in the inspection of tools, crankshafts, bearings and many small parts where residual magnetism is considered objectionable. It is rarely, if ever, necessary in the inspection of welds, castings and forgings.

Welded fittings for airplane structures, such as parts of landing gear and engine mounts, should be demagnetized. In some cases the entire welded fitting can be passed through a powerful alternating-current field of sufficient intensity to reduce the residual magnetization down to the level which is inherent in all steel parts due to the earth's magnetic field. In the case of the engine mount, special methods may be necessary such as winding a few turns of conductor around the part and progressively decreasing the flow of current through the demagnetizing turns. One method of demagnetizing complicated structures such as fuselages and engine mounts which has been found to be more effective than any other to date is that of passing an alternating current of high amperage and low voltage through as large a portion of the structure as is possible and gradually decreasing the current until a very low value is reached.

Equipment

For the inspection of railroad car and locomotive axles, the method supplies a simple and conclusive means for locating troublesome fatigue cracks which would eventually cause rupture of the axle. Special axle testing units to handle such inspection on a production basis have been constructed and are in use on many railroads. Crank pins, side rods, wheels and wheel centers, valve linkage members and many other parts are also being regularly examined, as well as new castings and forgings of many kinds.

For the inspection of welded seams and other field inspections on flat surfaces where it is necessary to employ circular magnetization by passing high-amperage current directly through the section, convenient leech contacts have been developed. By means of these, copper contacts can be quickly attached magnetically to any desired points on the steel structure. Power for both the hold-down magnets and the high-amperage current is supplied from the portable power unit. (Fig. 9) This unit may be either direct or alternating current. In the case of direct current a three-phase step-down transformer and heavy rectifier is convenient. On irregular shaped parts, where the leeches are not practical, current is usually led into the metal surface through heavy copper contacts firmly held by hand against the structure, these contacts being located one on each side of the weld and spaced from 3 to 6 or 8 in. apart, depending on the current available and the thickness of the metal. The direction of the current is then parallel to the weld and produces a strong magnetic field across the weld. Care must be used to prevent arcing and burning at these contacts. On high-carbon parts a contact burn may cause small hardening cracks at the burned spot. On finished work and wherever fatigue stress is expected, contact burns must be avoided and if they occur they should be ground out. In order to avoid these contact burns, it is necessary that the current be shut off without forming an arc at the contacts. Some form of circuit breaker is therefore necessary.

Whatever method is used for generating the magnetic field, reproducible results are only obtained when the magnetizing currents are themselves reproducible. All magnetizing equipment is furnished with an ammeter to record the magnetizing current, but in some cases there is a transient surge of current when the field circuit of the generator is completed. This

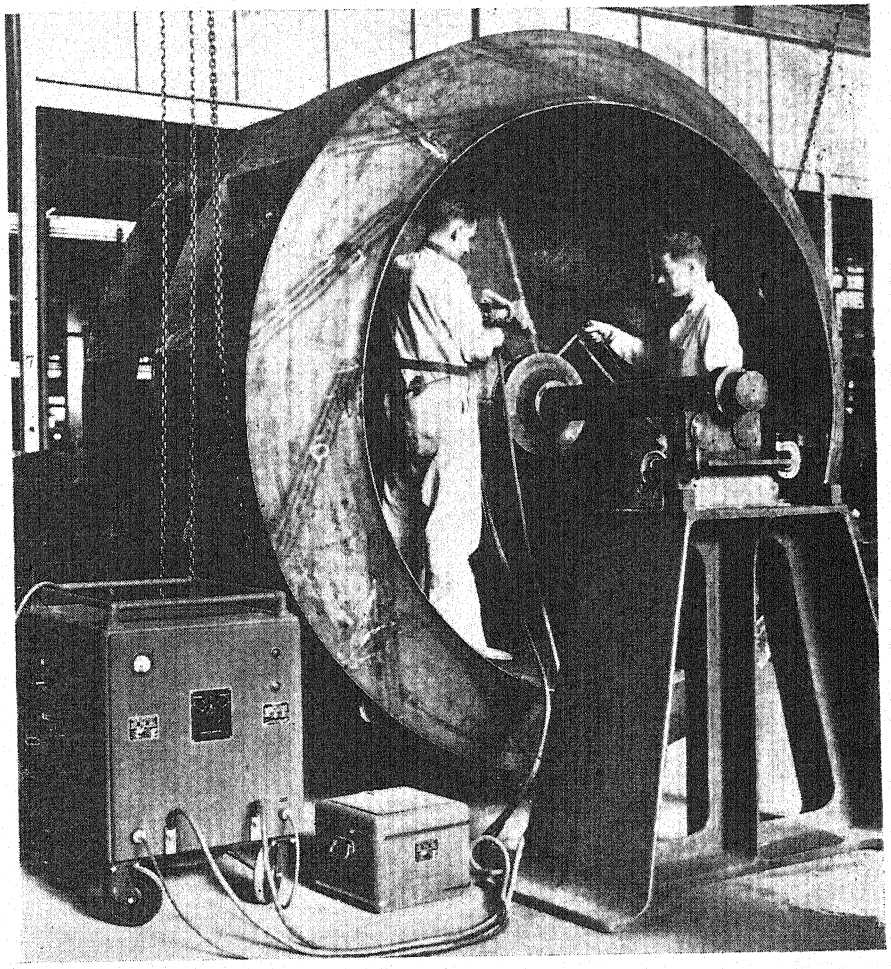


Fig. 9—Power Unit and Powder Blower in Use for Weld Inspection

is particularly true in the case of arc-welding generators and the extent of this surge is not measured by the customary ammeter. This overshoot or surge plays an important role in the magnetization level which is reached in the part and very greatly assists in the location of deep-seated defects. The resulting magnetization in this case will be greater than it is when the magnetizing current is reached gradually. In the latter case, only the magnetization caused by the 350-amp. steady flow is realized.

The amount of this surge depends largely on the characteristics of the current supply unit. In general, any change in current control will change the percentage of surge.

The type of generator used for arc welding supplies approximately six

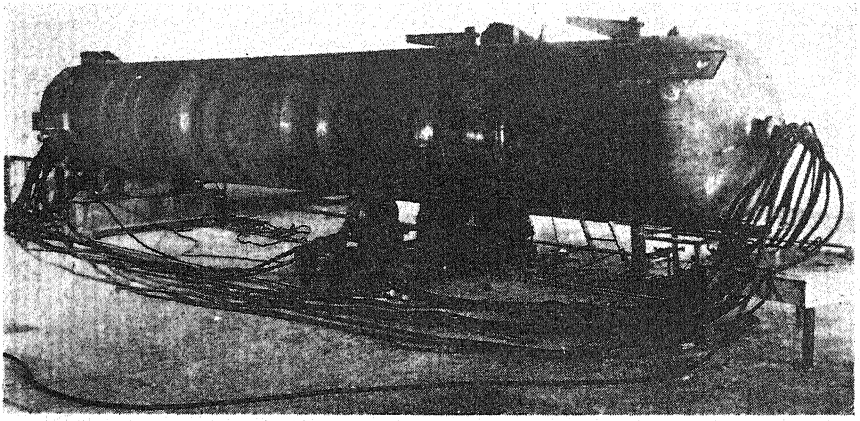


Fig. 10—Cable Method of Inspection Applied to Large Vessel

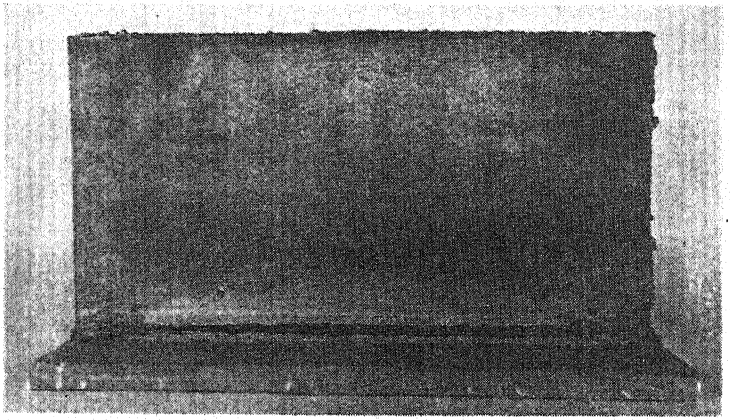


Fig. 11—Indication of Sub-Surface Defect in Fillet Weld

volts direct current under short-circuited conditions and may be used for this type of inspection. However, the characteristics of arc-welding equipment are such that if the resistance is increased by a bad contact a voltage of forty to sixty is supplied by the generator with a greatly increased tendency to produce contact burns. This tendency may be reduced by the use of lead-tipped electrodes. The current through the contacts must be interrupted either by a circuit breaker on the high-amperage output of the generator, or in the field of the generator. The switch in the field circuit is to be preferred from the point of view of reproducible results. Neither

form of current control is customarily supplied on arc-welding equipment and where arc-welding welders are to be used for magnetic powder inspection, control equipment must be added. There is now on the market low-voltage rectified alternating current equipment manufactured espe-

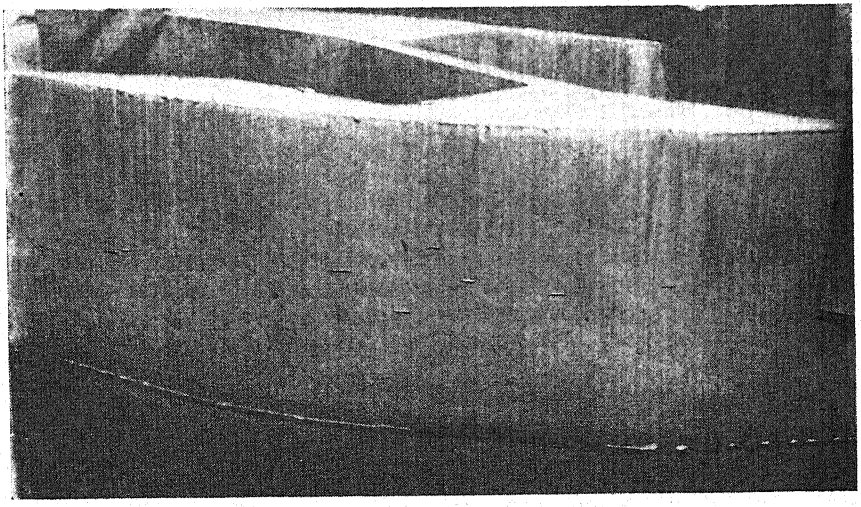


Fig. 12—A 5-In. Flame-Cut Piece of Plate Used in the Construction of Gun Mounts Showing Indications of Laminations. Inspection for Such Laminations Is Closely Associated with the Welding Field

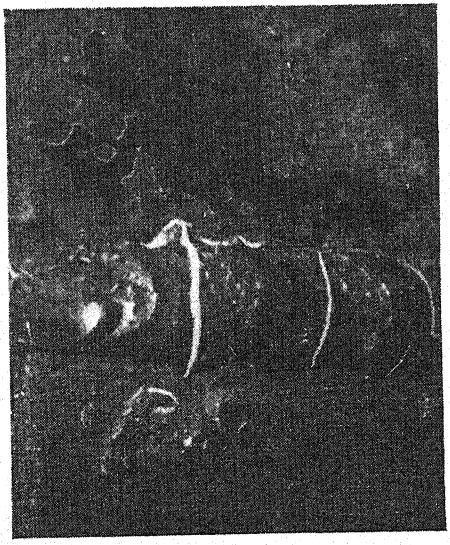


Fig. 13—Transverse Cracks in Weld

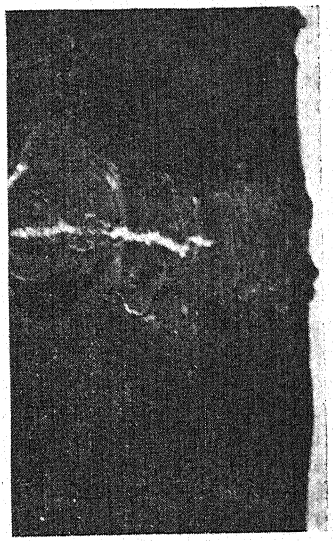


Fig. 14—Longitudinal Crack in Weld

cially for weld inspection, in which the peak output current can be diminished by a predetermined amount and after a predetermined time to produce the effects of a controlled surge.

For the inspection of complete welded structures, particularly tanks and boilers, the entire structure may be magnetized by wrapping cable around or through the center of the vessel. For instance, in Fig. 10, the longitudinal seams are inspected by producing a circular magnetic field by means of the cables threaded through the manholes. For transverse seams the cable would be wound helically around the outside. Welding generators are suitable for magnetization of this type as the danger of burning is obviated. In general, however, the wrapping method will not discover as deep-seated defects as will the contact method. It is to be noted, however, that the contact method only inspects a short length of weld itself. The wrapping method is, therefore, useful on complete objects.

Either the cable wrapping method (see Fig. 10) or the direct contact method is usually employed for such inspection, although portable electromagnets also find use in some instances.

RADIOGRAPHY*

Introduction.—Radiography may be defined as the art of making shadowgraph pictures by means of X-rays or gamma rays. It furnishes a very valuable method for non-destructive testing of metal within the limitations of its applications. The shadowgraphs obtained show subsurface details of gross structure. The method is applied to welds for the purpose of obtaining information regarding the soundness characteristics of the weld and adjacent plate metal; that is, as to the presence of defects such as gas cavities, non-metallic inclusions, lack of complete penetration, imperfect fusion and cracks.

The information obtained in this way is used principally for the following purposes:

1. For the acceptance of welds or welded structures subject to radiographic inspection.
2. For the development of welding procedures.
3. For the training and examination of welding operators.
4. For shop control of weld quality.

Code Requirements

The A.S.M.E. Code for boilers and Par. U-68 pressure vessels contains elaborate radiographic requirements. All longitudinal and circumferential welded joints in power boiler and certain pressure vessels must be radiographed throughout their entire length. The weld reinforcements must be removed to an amount not exceeding $^1/_{16}$ in. and the welds must have a smooth surface. X-ray films are designated "exographs" and those made with gamma rays, "gamma graphs." The technique employed in making the negatives must be such as to determine quantitatively the sizes of defects with thicknesses equal to or greater than 2% of the metal thickness.

* Approved for publication by Chief of Ordnance, U. S. Army.

Penetrameters are required and are described definitely. Specifie directions for their use are given. The Code requires that films be placed as close to the metal being radiographed as practicable. With films not more than 1 in. away from the metal surface, the tube distance, i.e., the minimum distance from the tube to the side of the weld nearest the source of radiation, is governed by the following table:

Plate Thickness in Inches	Tube Distance in Inches
Up to 1	14
1 to 2	21
2 to 3	27
3 to 4	36
4 to $4^1/_2$	38

Complete identification marks are required to be placed on each film. Location markers are required, the images of which must appear in the films and the positions of which are stamped on the metal surface.

The acceptability of welds, judged from radiographic negatives, is determined by comparing with a standard set of radiographs, reproductions of which can be obtained from the Boiler Code Committee. In general the requirements are:

1. There shall be no elongated slag inclusions of length greater than $^1/_3T$, where T is the metal thickness.
2. If the inclusions have length less than $^1/_3T$ and are separated by at least $6L$ of good metal, where L is the length of the longest inclusion, the weld is acceptable if the sum of the lengths of such inclusions is not more than T in a length of $12T$.
3. Cracks and zones of incomplete fusion are not acceptable.
4. Porosity is judged by reference to the standard radiographs.

The A.P.I.-A.S.M.E. Pressure Vessel Code is similar in these requirements to the A.S.M.E. Code.

The Bureau of Ships of the U. S. Navy has set up radiographic standards that are defined by type radiographs. These are for use in inspecting Class A-1 pressure vessel welds and all other welds intended to meet requirements of Class A-1 welding. These standards are used in connection with the current issue of the Bureau of Ships General Specifications for Machinery. Detailed radiographic requirements that include the standards are issued as parts of specifications that cover special structures.

The Ordnance Department of the U. S. Army has set up radiographic requirements in Specification AXS-476. This specification defines how radiographic inspection shall be carried out where required in contracts or purchase orders. It includes radiographic standards which parallel those set up by the code committees for pressure vessel construction. The various standards for highest quality welds are, in fact, essentially alike.

Development of Welding Procedure.—Radiography has one of its most important applications in development studies to establish welding procedures. It is true that other tests are needed to determine the strength, ductility and other intrinsic properties of the weld metal, but these intrinsic physical properties are largely dependent upon the proper selection of filler metal with reference to the plate material, upon the method of welding, and upon other factors that can be reduced to simple control. The radio-

graphic test gives information only as to soundness. This information, however, is highly important. The possible strength and ductility of the weld metal cannot be realized in service where extensive macroscopic defects exist. In general, the procedure that gives the soundest welding gives also the best weld. Where unsoundness is found in a weld which presumably has been made by a procedure which is known to have produced sound welds, it may be inferred that the developed procedure was not followed, and that, in consequence, other weaknesses than porosity may be present.

The use of the method for development purposes is quite simple. Pictures are made and the welding engineer analyzes revealed defects. Later he judges the efficacy of steps taken to correct defects by evidence obtained from negatives of the new weld. The study is empirical. This use of radiography permits considerable saving of time in the development of procedures, partly because several possible welding factors may be studied simultaneously, and partly because the pictorial representation of defects is more easily understood and, therefore, better understood than is less direct evidence obtained by other methods.

The Training and Examination of Welders.—The student welding operator is shown pictures of his work and defects are discussed with his instructor. The method enables the student to study and understand his errors, and presumably makes for more intelligent and rapid progress than other methods less adapted to pictorial representation. In qualification tests the candidate is sometimes required to produce sample welds that come up to established standards of soundness, as judged from the radiographic negatives.

Shop Control.—Where radiography is used in routine testing, the metallurgist, foreman or other responsible party may use the negatives for the purpose of checking the work of individual operators and also the work of the shop as a whole. In this way, weld quality may be kept up to predetermined standards of soundness. Procedure control mentioned above is also one kind of shop control.

X-Ray Equipment

Sources of Radiation.—X-rays become more penetrating with shortening of the wave length, which is inversely proportional to the voltage applied to the tube. To calculate the minimum wave length emitted by the X-ray tube, the following equation may be used:

$$\lambda \text{ min.} = \frac{1.234 \times 10^{-4}}{V}$$

where λ is the minimum wave length expressed in centimeters and V is the tube voltage. An X-ray tube working under 100 kv. gives, as its shortest emitted wave length, 0.1234×10^{-8} cm., or 0.1234 Å.* A 400-kv. tube gives X-rays of minimum wave length, 0.0309 Å. For 1000 kv. the minimum wave length would be 0.012 Å. Radium gives radiation which corresponds to X-rays generated with 2500 kv.

* The symbol Å is the standard designation for "Angstroms," a unit of linear measurement, 1 Angstrom = 1×10^{-8} cm.

In the welding shop, work may involve at times metal thicknesses of 4 in. or more, although the bulk of it probably falls under 2 in. For weld metal of 2 in. or under, a 200-kv. X-ray tube has been found to be satisfactory. For thicknesses above 2 in. and under 4 in., 400-kv. X-rays have been found satisfactory. Due to the fact that such X-rays generate excessive quantities of secondary radiation, it is necessary for best results to use a grid or filter when radiographing, to bring out fine detail. For thicknesses from 2 to 7 in., gamma rays or million-volt X-rays may be used. These have the advantage that no grid or filter is required.

Generating Equipment.—Tubes and auxiliary generating equipment, by means of which high-tension direct current is supplied to the tube terminals, have been greatly improved in recent years. Electric power is taken from transformers in some cases and the high-tension alternating current output is rectified. Originally, this was accomplished mechanically by a rotating switch. Many of these mechanically rectified installations are still in use. There is much to commend them. Although less efficient, they have the advantage of low maintenance cost and are nearly foolproof.

Kenetron† rectification has supplanted the simple rotating switch, with consequently more complicated electrical circuits and controls. More recent sets are self-contained units in which the X-ray tubes, the rectifying tubes and the transformer windings are all enclosed in an oil-filled metal case. In the latest developments "Freon gas" has replaced the oil as the insulating medium in the transformer case. This gas, especially when used under pressure, is more efficient as an insulator than oil and makes possible very great reductions in the weight of equipment. In fact, it has been very largely responsible for making million-volt equipment commercially practicable.

Million-Volt X-ray Unit.—The most outstanding development in X-ray equipment in recent years is the million-volt X-ray unit, a product of the General Electric Research Laboratories, that has been commercially available since July, 1941. This is a shockproof self-contained unit that weighs only around 1200 lb. and that can be angulated for any desired positioning. The pictures obtained with this unit are of excellent quality in comparison with those obtainable with lower voltage X-rays. Contrasts are at a lower level than those characteristic of lower voltage X-rays. Detail is as good, and sensitivity is superior for metal thicknesses above 3 in. The pictures also possess the advantages of those taken with radium, in that relatively large variations in metal thicknesses can be radiographed on the same film. With this radiation, it is possible to obtain pictures through metal thicknesses up to 8 in. in practicable exposure times. It is considered that the development of this tool has greatly enlarged the field of application for radiographic testing.

Diaphragms (or Grids).—Because of the effect of "secondary" radiation in concealing image detail, clear pictures are difficult to obtain through heavy metal sections when radiographing with X-rays generated at 400 kv. or under. This difficulty has been overcome to a considerable extent by the use of a device known as the "Buckey" diaphragm (or grid). This con-

† A Kenetron is a device for rectifying alternating current. It consists of a hot and a cold electrode enclosed in an evacuated tube. Since conduction through such a tube is by means of electrons given off by the hot electrode, current can pass only when the hot electrode is negatively charged. The device is so well known that a description of it seems to be unnecessary.

sists in principle of a grid of lead strips set on edge. The plane of each strip is parallel to the direction of the beam, and the strips are spaced so as to allow the primary beam to pass through the parallel spacings. The device is mounted immediately adjacent to the film and between the film and the metal surface. The primary radiation passes through the parallel slits, most of the secondary being absorbed by the lead grids. In the "Buckey" diaphragm, the grid is oscillated by means of a motor. This oscillation prevents, to a large extent, the images of the lead strips from appearing in the negative. In the Lyshom diaphragm, the grid is not oscillated. The images of the lead strips appear in the negatives, but for a great deal of work, do not interfere seriously with the reading of the negatives. The "Buckey" grid has been used to advantage in improving definition in radiographs of metal sections up to 5 in. It is, however, bulky, increases exposure time* and because of geometrical considerations cannot be used in many structures that have irregular shapes.

Filters.—The X-ray absorption coefficient for any given wave length increases rapidly with increasing atomic weight of the metal being radiographed. Thus, lead is relatively much more opaque than aluminum to a given wave length radiation. Also, for a given metal, the absorption coefficient increases rapidly with the increase in wave length of the radiation being used. Thus, lead is much more transparent to short wave, than it is to long wave length radiation. The radiation which reaches the film contains a mixture of wave lengths, the shortest of which is that of the primary radiation. The secondary contains much radiation of longer wave lengths. If a sheet of lead or other relatively high atomic weight material is interposed between the metal and the film, these different wave lengths will be absorbed differentially, so that the radiation which actually reaches the film contains a relatively higher percentage of the primary than would have been the case had no lead sheets been interposed. This differential absorption is known as "filtering," and the lead sheet used is called the "filter." The "filter" is less efficacious than the grid in reducing the bad effects of secondary radiation, but has the important advantage of much greater flexibility.

Intensifying Screens.—Normally, only about 10% of the X-radiation incident upon it is absorbed by the photographic film. The rest does no work in producing the picture. In order to utilize more of the radiation, devices known as intensifying screens are used. These are of two types, in the first of which fluorescent salts are used, and in the second of which the secondary radiation of a metal foil is used. The fluorescence from the screen greatly increases the effective radiation on the emulsion and contributes materially to the formation of the image. The intensifying factor is defined as the ratio of the exposure with the intensifying screen to the exposure without the screen to produce the same optical density in the negative. Exposure is defined as the product of the time and the milliamperes through the tube. The intensifying factors may be quite large. Tests under laboratory conditions have shown intensifying factors as great as 100; for shop conditions, they may be as high as 25, depending on the kind and condition of the screen. Exposures are shortened in proportion.

Intensifying screens must be handled with extreme care. The pure white contact surfaces are easily injured. Scratches, cracks, stains, etc., that

* Apparent increase partially deceptive.

may occur are transferred to the negative and serve to make interpretations more difficult. Most salt screens can be washed with soap and water if done carefully in accordance with manufacturers' instructions. The salt screen tends to cause loss of definition due to the fact that the light from the fluorescing particles goes out at all angles, so that the images seem to "spread." Because of the difficulties that have been encountered in the use of salt screens, there is a present tendency to avoid the use of them for all radiographic work where the best negative quality is essential.

Metal foil screens have the disadvantage that intensifying factors are much lower, but have the advantages that they are relatively inexpensive, are much more flexible and produce images with relatively sharp definition. The metal foil intensifying screen acts also as a filter, thus reducing the bad effects of secondary radiation. In recent years, their use has been growing in popularity for radiography with X-rays and for many years they have been regarded as the only practical intensifying screen for use with gamma rays. They are especially valuable for million-volt radiography. Foils of around 0.006 in. in thickness have been found to give good results for X-rays generated at voltages up to 400 kv. To obtain the best results the screen must be in very intimate contact with the film. Wrinkles and regions of poor contact show in the finished negative.

The combined effects of intensification and filtering are taken advantage of in some industrial screens where a lead foil may be combined with either a salt screen or a metal foil screen and in which case the filter is permanently mounted in the film holder (or cassette). One disadvantage of the lead intensifying screen is its tendency to oxidize. This has been overcome by the use of lead foil over which there is a thin coating of tin, the tin plate tending to resist oxidization.

New Radiographic Films.—Various improved films have been developed for radiography. Films of one of these types, marketed under the trade name of "No-screen" or "Non-screen," have the properties that they are peculiarly sensitive to short wave length and are less sensitive to long wavelength radiation. These can be used for steel sections up to $^5/_8$ in. in thickness without salt intensifying screens. They can be used to advantage with metal foil intensifying screens, and when so used, are applicable to metal sections up to 1 in. in thickness. Another film has been developed for use with gamma rays that will permit the reduction of exposure times by a factor of approximately two-thirds of that required for films previously used. This film is coarse-grained and the grain of the film interferes to some extent with the rendition of fine detail in the negative. A third film has been developed especially for bringing out fine detail. This film has a very fine grain and gives negatives of remarkable clarity. It has the disadvantage that exposure times are greatly increased. This film seems to be an ideal one for use with million-volt X-rays. The increase in exposure time in this case usually is not a serious disadvantage.

Gamma Ray Radiography.—Gamma radiation is obtained from various radioactive substances. Radium and its emanation, radon, are the only two of practical importance for radiography. Radium disintegrates at a constant rate into helium and radon, both of which elements are gases. During disintegration, radiation is given off. This radiation is of ex-

tremely short wave length relative to that of ordinary X-rays and constitutes the gamma rays familiar to radiologists.

Radon is itself radioactive, breaking down into other elements, some of which are radioactive, and giving off gamma rays. It can be trapped and used as a source of radiation in radiography, but it has the disadvantage of a relatively short life, the intensity of its radiation decaying to half value in 3.82 days. Radium, in the form of a salt, contained in a capsule in equilibrium with its disintegration products, is accurately constant in the intensity of its radiation, and from this standpoint is a better source for radiographic purposes. Gamma rays correspond to X-rays generated at approximately two and a half million volts. They are far more penetrating than X-rays and have the peculiar property that they do not produce scattered radiation in any considerable quantity. Because of this fact, the elaborate protection of the film against the bad effects of scattered radiation which must be observed with the longer wave-length radiography need not be observed with gamma rays. Contrasts obtainable in gamma graphs are of a lower order than those obtainable in exographs. Detail, however, is about the same in both cases. It results, therefore, that details are as faithfully reproduced in the gamma graph as in the exograph, but due to differences in contrast, the gamma graph gives an entirely different appearing negative. The lower contrast in the gamma graph makes it possible to picture large variations in metal thickness on the same film. This is a particular advantage when radiographing such difficult items as fillet welds. Radiographic sensitivities obtainable with gamma rays are inferior to those obtainable with X-rays when radiographing metal sections up to approximately $2^1/_2$ in. They are definitely superior to those obtainable with X-rays (taken without the assistance of a grid) for metal sections above 3 in. For sections as great as 4 in., 1% sensitivity with gamma rays has been reported. Gamma ray radiography has an added advantage in that the equipment required is extremely simple. It has the great disadvantage that extremely long exposure times are required, and for this reason the method is not practical for many applications where results are relied upon for shop control of weld quality. Most of the advantages of gamma ray radiography are realized with X-ray radiography, utilizing one million-volt X-rays, and in addition the million-volt radiographs can be made with practical exposure times.

Health Protection.—Constant exposure of the human body to X-rays or gamma rays is injurious to health. For this reason it is necessary to protect operators and others who may be working in the vicinity from the radiation. Protection is effected in several ways: first, the source of radiation may be confined within a suitably protected room; second, absorbing screens may be placed around the work so as to intercept the radiation; third, workers may be kept at a sufficient distance to protect them from any stray radiation; and fourth, no attempt is made to absorb stray radiation, but exposures are made at times when no workmen are in the vicinity.

Where the source of X-rays is confined to a room, protection is secured by lining the room with lead or making the walls of a material that will have an equivalent absorbing power. An excellent discussion of the subject of X-ray protection is contained in the National Bureau of Standards Handbook, HB20, which may be obtained from the Government Printing

Office.* Table 1, taken from this publication, is reproduced below. It gives the lead equivalent to be used in protecting walls of X-ray rooms.

Table 1

(From National Bureau of Standards Handbook HB20)

X-RAYS GENERATED BY PEAK VOLTAGES NOT IN EXCESS OF	MINIMUM EQUIVALENT THICKNESS OF LEAD	X-RAYS GENERATED BY PEAK VOLTAGES NOT IN EXCESS OF	MINIMUM EQUIVALENT THICKNESS OF LEAD
75 kv.	1.0 mm.	225 kv.	5.0 mm.
100 kv.	1.5 mm.	300 kv.	9.0 mm.
125 kv.	2.0 mm.	400 kv.	15.0 mm.
150 kv.	2.5 mm.	500 kv.	22.0 mm.
175 kv.	3.0 mm.	600 kv.	34.0 mm.
200 kv.	4.0 mm.		

Table 2†—Lead

POTENTIAL KV.	THICKNESS, MM.
100	1.5
200	4.0
300	9.0
400	15.0
600	34.0
1000	86.0
Gamma rays‡	100.0

† Table 2 is taken from an article by LAURISTON S. TAYLOR, "Industrial X-ray Protection," *ASTM Bulletin*, p. 26, August 1939. The thickness of concrete required for protection when using 1000-kv. X-rays is given in the curve of Fig. 15.

‡ 100 mm. applies to 3 g. of radium at a distance of 100 cm.

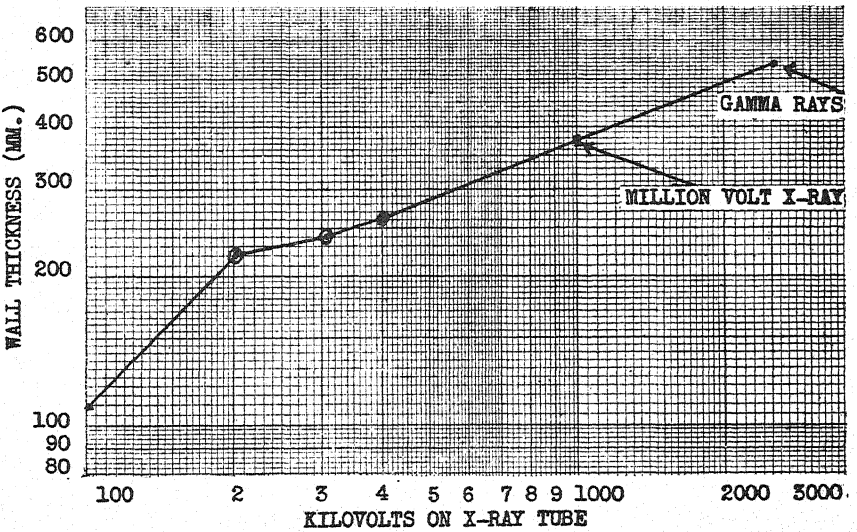


Fig. 15—Recommended Concrete Wall Thickness

* See also TAYLOR, L. S., "X-ray Protection," *American Journal Roentgenology and Radium Therapy*, XXVI, No. 3 (September 1931). This contains the same material as HB20 and was prepared by the same author.

The protection that has been used for million-volt X-ray installations in a number of industrial installations is 18 in. of well-compacted concrete.

Where the source of radiation is not confined to a protected inclosure, workmen must be kept at a distance from the radiation. Medical radiologists have determined that a safe tolerance dose of radiation is $^1/_{10}$ Roentgen.* This means that a workman exposed to radiation should not accumulate more than this quantity of radiation in one eight-hour working day. There are at the present time dosage meters† available which measure the radiation intensity at a particular location. One of these instruments is calibrated to read in terms of total radiation per eight-hour day. When the meter reading is 50, the total radiation in eight hours would be $^1/_{10}$ Roentgen. For radiation intensities that give readings above 50, the field is regarded as unsafe for workmen who would be stationed at that locality for a period of eight hours. This instrument is equipped with a red signal light which flashes when the meter reading exceeds 50. In practice, when using this instrument, radiation fields in the vicinity of the work are measured for different points, and a rope may be stretched to prevent workmen coming within unsafe distances.

The National Bureau of Standards Handbook HB20 gives rules for protection of operators that should be observed. It recommends that periodically operators be required to wear a dental film. One-half of the film is covered by lead foil. The film packet is worn on the chest, film side out, for fifteen working days. If upon development, the exposed part shows appreciable darkening, the cause is to be investigated and eliminated.

It further recommends that all persons engaged in radiological work be examined yearly for general radiation injury and that complete blood counts be made bi-monthly. The results of all tests and examinations should be permanently recorded. Blood counts may be made by any competent physician, but the same man should make the successive tests, or else have available all previous records.

X-Ray Technique

Technique may be defined as the complete series of operations that the technician executes in securing a finished radiographic negative. There are some differences in procedure for X-rays and for gamma rays.

Space limitation prevents an adequate treatment of this important subject. Some features of it will be discussed here. For more complete information, the reader is advised to consult standard publications.‡

Procedure may be divided broadly into the following headings:

1. Preparation of specimen.
2. Preparation of film.

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* "The quantity of gamma radiation received in one hour at a distance of one centimeter from a point source containing one milligram of radium element surrounded by 0.5 mm. platinum may be regarded as approximately equivalent to eight Roentgens" (ROBERTSON, *Radiology Physics*, p. 183).

† Dosage Meter, the Geophysical Instrument Company, Washington, D. C. A similar instrument is marketed by the Electronic Control Corp., Detroit, Mich.

‡ See NORTON, J. T., "The Principles of the Radiographic Process," *Symposium on Radiography and X-ray Diffraction*, A.S.T.M., 1936; *X-rays in Industry*, Eastman Kodak Co., 1930; ST. JOHN AND ISENBURGER, *Industrial Radiography*, 1934; MOCHEL, N. L., "Gamma Ray Radiography and Its Relation to X-ray Radiography," *Symposium on Radiography and X-ray Diffraction*, A.S.T.M., 1936; GEZELIUS AND BRIGGS, *Radium for Industrial Radiography*, available through Radon Co., 1 E. 42nd St., New York City; PULLIN, V. E., *Engineering Radiography*, G. Bell & Sons, Ltd., 1934.

3. Protection against secondary radiation.
4. Exposure.
5. Development.
6. Examination of negative.

Preparation of Specimen.—This operation consists in locating areas to be examined, in attaching identifying markers, penetrameters, etc. The identification of areas is of sufficient importance that it is sometimes covered in specifications. Welds to be examined are sometimes numbered serially and locations on each weld are designated. As an example, 10-4 might represent location number 4 on weld number 10. It is usually required that each negative shall carry complete identification which may include the serial number of the piece, the weld and location number and the position marker. The position marker may be a lead arrow or triangle, the image of which appears in the film and the location of which is marked on the piece by prick punch marks. The identification numbers are lead numerals which may be attached to the metal by wax. These may be used for position markers.

The selection of areas to be examined depends somewhat on the use that is to be made of the results. In pressure vessel work, all of the welding may be radiographed. In other work, radiographs are often indicated in the original drawings or otherwise located by competent engineering authority. Other pictures may be requested by the inspection service to determine the general character of the welding, and still others may be required by the shop superintendent for purposes of special information or control checks. It is usually not the duty of the radiographic technician to designate locations. It is his duty to spot the locations called for on the piece and to expose so as to get the best picture. Positioning of the work with reference to the direction of the radiation is quite important. It often happens that pictures have to be made at difficult angles. The film may at times be placed so as to catch the X-ray beam almost at grazing incidence. Images are, of course, distorted, but are valuable provided they are read with full knowledge of how they were taken.

The distance of the source of radiation from the film is another point of procedure that must be considered. Radiation proceeds not from a point, but from a definite area on the X-ray target or from the volume of the gamma ray capsule. It has been found experimentally that for most commercial X-ray tubes of voltage below 400 kv., the distance of the tube from the work should be governed by the following ratio:

$$\frac{d}{t} \text{ is equal to or greater than } 15$$

where d is the distance from the source of radiation to the adjacent metal surface, and t is the distance of the film from the same surface. Million-volt X-ray tubes have a variable focal area. The proper d/t ratio for such tubes depends upon the particular size of focal area used. In general, the d/t ratio should be as great as possible, consistent with practical exposure times. Where d/t values less than the optimum are used, pictures may be obtained which in many cases are adequate for the purposes intended, but fine detail will be lost so that fine cracks which might be present probably would be undetected.

Preparation of the Film.—The film should be numbered and dated before exposure. Where fixed cassettes are used, it is placed in the cassette between the intensifying screens, and the cassette is ready for use. In complicated structural work films are often bent to fit difficult contours, or must be placed in spaces too small to accommodate cassettes. In such cases, the intensifying screens, with the film between, may be made up into a package. A sheet of lead about $^1/_{32}$ in. in thickness is placed on the side remote from the source of radiation and cardboard or other stiff material such as vinylite is placed outside of the lead sheet, and the assembly wrapped in black paper. The package is placed in position and held in place by wooden props or wedges. The vinylite distributes the pressure from the supports and holds the film in intimate contact with the intensifying screens. Copper or brass plates can be used instead of vinylite, but are apt to become dented in use.

If Buckey diaphragms are not employed, filters should be used where the metal thickness exceeds 1 in. These may be included in the film package. They are placed outside of the intensifying screen on the side of the film toward the radiation.

The film package contains a lead backing, but this is not sufficient when radiographing with ordinary X-rays. Additional lead must be placed so as to intercept all possible secondary radiation from sources other than the material being radiographed. A study of the set-up for possible leaks will, in many cases, save the expense of retakes. When radiographing with gamma rays, there is a certain amount of reflection from the walls of the chamber in which the work is done, so that in this case also, it is advisable to have lead back of the film.

Exposure.—Proper exposure may be determined roughly by exposure charts, a number of which have been published, but there are many factors which govern. The type and condition of intensifying screens, the absorption of the filter or the Buckey grid, and the characteristics of the X-ray machine are some factors that affect the chart readings. Experience is the most reliable guide.

Development.—The dark room technique is similar to that for ordinary photography and is sufficiently well known that no detailed descriptions are necessary here. The dark room should be conveniently large and should be laid out with care. Tank thermostats are recommended to keep the solutions at a constant temperature. The addition of potassium iodide to the developer in accordance with manufacturers' instructions has the advantage of retarding chemical fog and hence, permitting longer development time. This longer time accentuates contrasts.

Keeping solutions uncontaminated is a matter the importance of which needs no urging. Keeping the developer up to strength is a matter the importance of which does need special emphasis. Recent tests in a large plant that makes extensive use of radiography showed that films developed in nearly exhausted developer had lost all fine detail, even though they showed the same optical density as those developed in fresh developer.

Examination of Negatives.—There is an optimum illumination for a given negative density which, when used in viewing, causes image details to stand out that are lost, because of glare, when an incorrect illumination is used. The reading of films requires concentrated attention, and proper

lighting conditions are essential. Where possible there should be provided a well-ventilated room, capable of complete darkening, that is supplied with illuminators designed to insure that all the light that reaches the eye comes through the film. Dimmers should be provided in the light circuits; the proper film illumination often may be secured simply by holding the negative at greater or less distances from the light. The care with which films are read depends to some extent on the nature of the information sought. Where fine detail is required, some time must be allowed for the eyes to become accommodated to the light.

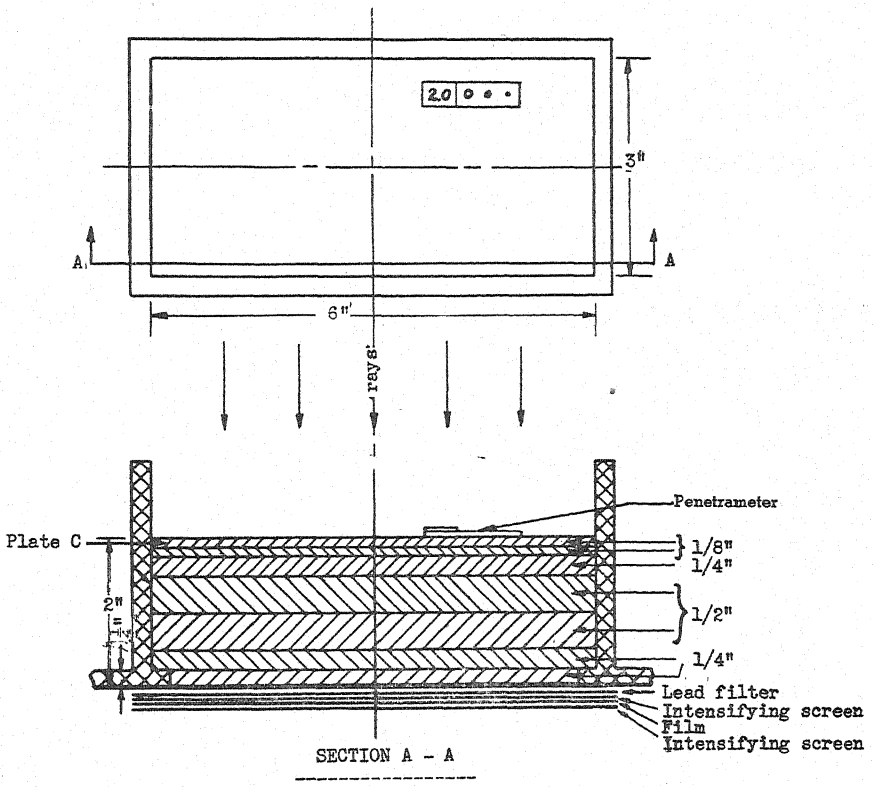


Fig. 15A—Diagrammatic Sketch of Radiographic Test Block

After image details are noted and proper records made, the negatives should be compared directly with the welds radiographed. The defects noted should be charted on the work.

It often happens that information is desired as to the depth of a flaw below the surface. St. John and Isenburger* and Dr. J. C. Hodge† have described simple two-exposure methods that permit depth calculations

* *Industrial Radiography*, p. 103.
† *Symposium on Radiography and X-ray Diffraction*, p. 80.

using only one film. Another method involves the making of two negatives. The depth is calculated from geometric construction, using a point of reference on the surface. C. D. Moriarity* has developed an ingenious stereoscopic arrangement and by means of reference planes drawn in the image, is able to locate defects with reference to those planes with a fair degree of accuracy.

The Test Block

Dr. C. A. Adams, Chairman of a special committee of the A.S.M.E. Boiler Code Committee on Radiographic Examination of Welded Joints, has suggested a device for testing radiographic technique. This device is a test block. It consists essentially of a stack of steel plates that can be adjusted to desired thicknesses. Some of the plates contain artificial defects, such as cracks. Provision is made for a penetrameter. (See Figs. 15A and B.)

In practice, the manufacturer under X-ray specifications must produce a radiograph of the test block in which the images of the artificial defects

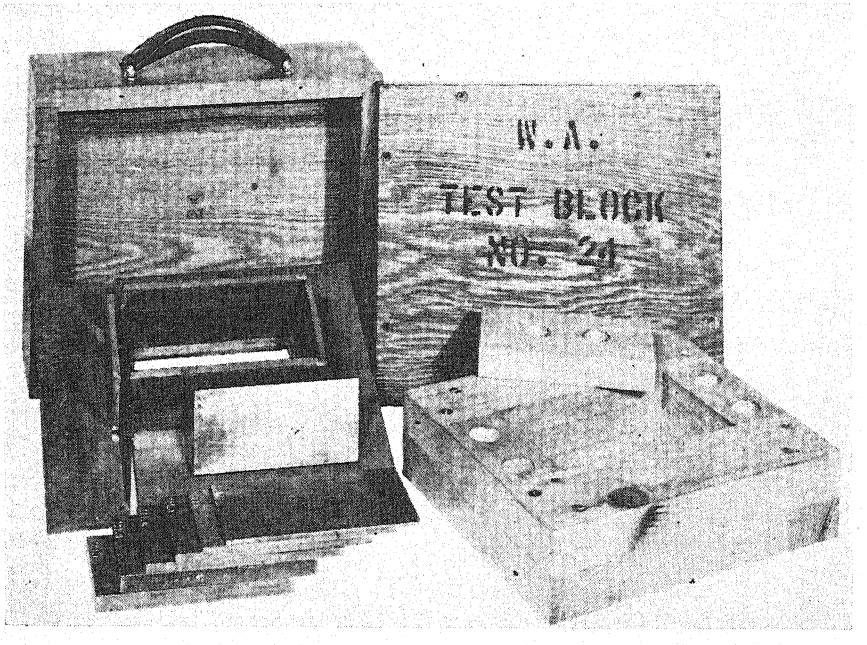


Fig. 15B—Test Block Supplied for Radiographic Qualification for Inspection by Army Ordnance

and of the penetrameter appear with clarity equal to those in negatives accepted as standard for the test block. This device tests both the X-ray machine and the operator. No restriction is placed on the technique employed, but the machine must be of sufficient power and the operator must have sufficient skill to produce the required results.

* *General Electric Review*, Nov. 1936 and Feb. 1937.

The Penetrameter.—In connection with the test block, the penetrameter is used to test sensitivity and also radiographic technique. Its principal use is in connection with production work and is to test whether or not the technique in the production weld was the equivalent of that used in making pictures of the test block. In practice, the penetrameter is placed on the metal surface remote from the film in each production exposure.

The ability of the observer to detect the penetrameter image depends not only upon the degree of contrast, but also upon the area of the image. In addition to this physiological effect, there is another, the "pinhole" effect. That is, a cavity in metal acts much the same as a "pinhole" in a pinhole camera. The image recorded in the radiographic negative is really a series of overlapping images of the source of radiation. When the cavity is small with reference to the size of this source, there is recorded not an image of the defect, but an image of the focal spot of the X-ray tube or an image of the radium capsule. Hence, there is a limit to the cross-sectional area of a cavity that will be truly represented. This limit depends partly upon the distance of the image from the film. Evidently it is a point that should be considered in judging radiographic sensitivity.

The penetrameters at present standard in the Boiler Code for plate up to and including $2^1/_2$ in. consist of a piece of metal of the same type of material as that being radiographed and of dimensions $^1/_2$ in. wide by $1^1/_2$ in. long, of uniform thickness, equal to 2% of the thickness of the metal being radiographed, and containing three holes which are, respectively, two, three and four times the penetrameter thickness but in no case less than $^1/_{16}$ in. A different penetrameter is used for each metal thickness to be radiographed. For plates thicker than $2^1/_2$ in. each penetrameter is required to be $2^1/_4$ in. long and 1 in. wide.

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CHAPTER 33C

TESTING OF WELDS—CORROSION*

Aims of Testing, Types of Tests, Corroding Media, Preparation of Specimens, Conditions of Testing, Determination of Results, Corrosion-Fatigue, Steel, Stainless Steel, Aluminum and Aluminum Alloys, Copper and Copper Alloys, Nickel and Nickel Alloys, Combination of Any Base Metal or Weld Metal Produced by Any Welding Process.

ANY lack of homogeneity in a metal may provide a cause for attack by corrosion, and complete uniformity in the material is interrupted in various respects by the presence of a weld. This may be illustrated by differences in metallographic structure, by variation in the nature or extent of surface oxidation, or by unrelieved stresses produced by the thermal changes that accompany the welding operation. Because of the irregularities that may be present, corrosion testing generally should be applied to the entire joint rather than to all-weld-metal specimens, although for specific purposes the base metal and weld metal are tested separately. The principles that govern the corrosion testing of metals in general need to be observed in the testing of welded specimens, and since the requirements in corrosion testing are exacting, the value of the results obtained will depend on the experience and carefulness of those who carry on the work.

The many factors that may affect the results make it important to observe a large number of details that are beyond the scope of complete description in this chapter. Great assistance can be obtained from the literature on corrosion testing. There are numerous standard works[1] on corrosion, and American Society for Testing Materials' publication, "Symposium on Corrosion Testing Procedures"—1937, is particularly recommended both for its excellent content on the subject of corrosion testing and for the extensive bibliographies that are included.

Many welded structures contain weld metal that is reheated, as at a cross weld, or at the finishing point of a circular weld. This reheating may affect the corrosion resistance of the weld metal (unstabilized stainless steel is an example); also, circular or cross welds produce stresses that may influence the corrosive attack. To investigate these factors, specimens of unwelded base metal and specimens of the same base metal containing circular or cross welds may be subjected to the same tests to give comparisons that will show any effects of the welding on the corrosion properties.

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When the suitability of a metal or alloy has been established for a given service, in many cases it is only necessary to find whether this same material is still satisfactory after welding. There will also be need to test the effectiveness of methods used to correct any harmful results associated with the welding operation. Certain corrosion tests of a metal or alloy have proved successful and have been standardized. The effect of the welding on the base metal and any variation in quality of the welds that would affect corrosion properties, at times may be determined by such appropriate tests under the more or less arbitrary but reproducible conditions imposed. These tests are used even though the conditions employed may be quite different from those likely to be encountered in service. The relationship between the results obtained with a given welded material in the adopted test and in service under given conditions of corrosion are determined and then the adopted test is used in any further testing of the material for the given service. Thus, data can be assembled through which one standard test may be used to show the corrosion properties of one or more materials in a variety of service conditions. However, there are many cases in which the only satisfactory tests are those in which the service conditions are duplicated.

Aims of Testing

The aims of corrosion testing are:

(1) To find a welded joint to withstand a given environment;
(2) to determine whether a given weld will stand certain corrosion conditions;
(3) to determine whether the weld metal is more or less resistant than the parts welded together, or
(4) to check the corrosion resisting quality of the welded metal in a suitable test.

Usually, the weld will be tested under the conditions to which it will be exposed in service, or in a laboratory test to check the probable performance in that service. The testing should provide a means of determining the effect of the welding process employed, the filler metal applied, the design of weld, and the technique of welding, on corrosion resistance of the weld, particularly in comparison with the same metal or metals not welded together.

Types of Tests

Laboratory Tests.—Many corrosion tests carried on in laboratories are designed to determine in a relatively short period, which may be a matter of days or even months, information that could be secured by use of the welded materials in service only when the structure was worn out or had failed due to corrosive attack. In many of these tests the corrosive action is not speeded up to any considerable degree, but by careful determination of slight corrosive attack it is possible to estimate with a reasonable degree of accuracy the relative life of the welded metals tested. However, at times, accelerated corrosion tests are carried out with useful results. At other times laboratory tests are employed as routine tests of metal quality and as a means of gaining an idea of probable behavior in a variety of environments. Laboratory tests have the advantage of being subject to careful control.

Field Tests.—In field tests the specimens to be tested are exposed in the location in which it is desired to use the welded metal but they are not made a part of any operating equipment.

Service Tests.—Tests in actual service can be carried out by installing welded metal parts in an apparatus that is being used under conditions in which resistance to corrosion is needed.[2]

Corroding Media

Atmosphere.—Metals exposed in the atmosphere are generally provided with some protective coating such as paint or corrosion-resisting metal. Corrosion tests then become largely a matter of testing the protective coating, and generally, the only useful purpose of testing weld metals in the atmosphere would be to determine whether the joint was in suitable condition to receive the proper application of the coating.

Water.—Exposure in water of desired composition is one of the most frequently employed methods of corrosion testing of metals, especially ferrous materials. In such testing the specimen may be entirely immersed, partially immersed or moved alternately into the water and into the surrounding air. Experience indicates that the complete immersion gives the most information about under-water corrosion. In a special case of corrosion testing by exposure to water, the welded metal is buried in corrosive soils under conditions that are representative of those expected in service.

Chemical Solutions.—Welded metals may be subjected to test by attack of certain chemical solutions generally used for the purpose of investigating some special properties of the metals in respect to their corrosion resistance. Here again, the metal may be completely submerged in the liquid, or partly in liquid and partly in atmosphere above the liquid, according to the service requirements. When strong chemicals are used, this atmosphere may have corroding properties due to the vapor evolved.

Preparation of Specimens

Standardization of specimens to be tested, especially in any given series of laboratory tests, is desirable. Usually such specimens will consist of strips of metal cut transversely to the weld. They should include the weld, with its adjoining heat-affected metal, and some of the metal at sufficient distance from the weld to provide base metal that has not been altered in its metallographic structure or its surface condition by the welding. The size and shape of the specimen should be selected so that the total area of the weld metal will not exceed about 10% of that of the whole specimen in order to provide an opportunity for the observation of the magnitude of any galvanic effects between weld metal and parent metal. It is important in corrosion testing as in service, that any residual welding flux be completely removed. This applies especially to aluminum and aluminum alloys. Since the nature of the oxide on the surface of the metal is frequently of importance in its effect on resistance to corrosion, some corrosion tests of welds will require that the original surface of the welded metal be left intact. Other welds, especially if weight loss is to be measured, will need to be machined all over and finished by grinding, so that a uniform condition of surface may be secured, and the area exposed to the corroding media

may be easily determined. In some tests involving weight loss the specimens should consist entirely of weld metal and, if desired, they may be compared in corrosion resistance with similar specimens of base metal. The surface of a specimen of this type is also of importance because irregularities, even as small as a deep scratch, may frequently have considerable bearing on the results. Polishing, passivation or other surface treatment must also be taken into account. This surface condition may determine where the corroding attack will start and may have a considerable effect on corrosion products such as surface films that are formed, which generally are effective in proportion to their continuity. After the grinding, the specimen should be properly cleaned by washing to remove grease or other foreign matter and then subjected promptly to the corrosion testing before atmospheric action on the surfaces can take place. Suitable means of supporting the test specimen must be provided. Generally, metals tested in liquid media are supported on hooks or rods made of glass, and a metallic support of any kind is always avoided.

Special preparation is required in corrosion testing of clad metal such as nickel clad steel or stainless clad steel. The test specimen is prepared by welding pieces cut from the clad plates after which the steel base is removed from the back of the specimen by machining or grinding followed by immersion in hydrochloric or sulphuric acids in the case of nickel clad steel or nitric acid for the stainless clad steel. This preparation avoids the uncertainty introduced by reliance on protective coatings applied to the steel back and edges of welded clad test specimens.

Conditions of Testing

For successful results in laboratory corrosion testing, control of the more important factors is imperative. In this control, especially as related to liquid corrosion tests, the important factors are: composition of liquid, temperature, oxygen concentration, motion and time. In some cases stress of the welded metal is included as a special test condition. The choice of conditions usually will be guided to a considerable extent by the actual service to which the welded metal is to be subjected, and generally the conditions of testing should be such as to produce a moderate attack in a reasonable test period. Tests that are accelerated enough to cause rapid attack are often accompanied by difficulties in measuring the extent of corrosion and in evaluating the results in terms of serviceability of the welded metal.

Temperature.—In most cases an increase of temperature leads to more rapid attack on the metal by corrosion, so results at one temperature may be quite different from those obtained at another temperature.

Composition.—Many immersion tests are made in tap water such as is obtained from city water supply systems. At other times chemical solutions, generally in dilute form, are employed. The solution chosen should be of the same composition that is contemplated in the service of the welded metal. Systematic replenishment or change of the solution to maintain a constant composition is a necessary part of the testing because changes occur in the composition due to evaporation and chemical reactions.

Oxygen Concentration.—The most satisfactory method of controlling the concentration of oxygen in the corroding solution is to bubble air through

the solution to keep the solution saturated with oxygen. The air should be diffused through the solution as fine bubbles. None of the air bubbles should impinge on the test specimen. Sometimes the same degree of aeration to be encountered in service should be aimed for but if this is not desired then either full aeration or complete absence of air should be employed. The latter is frequently used in testing of stainless steels.

Motion.—Motion of the corroding liquid in respect to the specimen under test frequently has a great influence on the result by removal of films, and this condition may be controlled in accordance with the expected conditions of service. The motion may be produced by the bubbled air or by rotation of the specimen. Conditions can be set up to duplicate high velocity of the liquid which may hasten corrosion by removing a corrosion product that would serve to retard further corrosion.

Time.—The corrosion test is sometimes carried on in a single period but usually there are several periods. Examination of the test specimen and determination of various effects of corrosion such as weight change can be made, and the relative amounts of corrosion in the successive divisions of the total time period found; thus any trend in respect to change of corrosion rate may be discovered. A number of specimens proportioned to the number of divisions of the test period may be immersed in the same bath. At the end of each division of the test period, two or preferably four specimens can be removed, examined and not returned to the corroding solution. Any effects due to removal of deposits from the metal surface and handling during the test can be avoided by this procedure.

Stress.—In welded structures the presence of locked-up stresses is an ever-present possibility, unless adequate precautions can be taken to reduce the stresses by heat treatment. These stresses may have a specific effect on the corrosive attack, depending on the environment, which may be either a simple acceleration of the rate of attack or either inter- or intragranular cracking. Tests of the effects of such internal stresses can be made by forming a sample of the steel or alloy into a simple horseshoe shape, bending the sample elastically with a clamp or other device, and subjecting the sample to the environment. The effect of stress on the rate of attack can be determined by losses in weight, as compared to similar losses when unstressed. The effect of stress in producing cracking can be told by simple inspection for cracks after a suitable length of time in the environment. Microscopic examination of a section through the crack reveals its path, either between or through the grains.

Determination of Results

Visual Examination.—The specimen when removed from the corroding solution should be examined to determine the nature of the products of the corrosion and to find whether the attack was uniform or localized in small areas. Local attack of a nature that results in the formation of pits frequently occurs. The visual examination often may be supplemented with advantage by macroscopic or microscopic examinations of sections cut across the weld.

Weight Change.—Change of weight, especially when corrosion attack has been uniform, is an effective means of determining the rate of corrosion. Weight change determinations of specimens containing both weld metal

and base metal will not give a quantitative measure of the extent of attack on the two parts of the welded specimens. This can be accomplished by employing separate specimens of base metal and all-weld metal. The units of measurement most frequently used are: penetration in inches per month, or milligrams per square decimeter per day.

Measurement of Pitting.—If the corroding attack takes the form of pitting, its extent is generally judged by means of visual examination and surface exploration to determine the number and depth of the pits. Number of pits per unit area, the maximum penetration and the average penetration are recorded. Sometimes the extent of pitting may be determined most satisfactorily by microscopic examination of cross-sections cut from the specimens; also, the type of attack may be determined by this means. On thin specimens, tension tests are often the best means of evaluating the overall effect of corrosion.

Tension Tests.—When strength of the welded metal is important to its service, it is highly desirable to subject tensile specimens to the corrosion tests so that the effect of corrosion on the strength of the specimens can be determined. These tests usually are applied to flat specimens which are oversize in width to provide for machining the edges after exposure to corrosion. Thus extreme effects due to localized attack on the edges will be eliminated. If there is pitting attack its effect on the strength of the welded part can be determined by tensile tests of corrosion specimens.

Corrosion-Fatigue

It has been well established in alternating stress tests that specimens subjected to a corroding medium during the testing generally will suffer considerable reduction in their resistance to repetitions of stress in comparison with similar specimens tested in the air. The effect of corrosion on metals subjected to alternating stress is called corrosion-fatigue. If the specimen is subjected to the action of corrosion before the testing, there will be some lowering of its resistance to fatigue failure but the change will not be so marked as is the case under simultaneous action of corrosion and fatigue. Corrosion-fatigue tests are generally applied to tapered specimens of the cantilever beam type that are mounted in a rotating fatigue testing machine. The main effect of application of repeated stresses on the rate of corrosion attack is considered to be due to the destruction of films of the corrosion product that form on the surface of the specimen. For this reason, not only are the number of cycles and the stress of importance but also the frequency of the cycles. In subjecting the welded joint to corrosion-fatigue tests, usually specimens machined from the weld will be compared with other specimens from the base metal but at times a transverse specimen with the weld placed at the point of maximum stress may be preferred. Details of the machining of the specimens, as well as information about carrying on the tests, are included in the published works of McAdam, Moore and others.[3]

Corrosion Tests of Steel

Corrosion tests generally applied to steel are: total immersion in water and alternate immersion in water. In the total immersion tests the water

should be aerated and the controls already referred to should be employed in both methods of testing. The salt spray test is used at times but in most cases this test should also be accompanied by other tests because strongly accelerated tests frequently are of doubtful value.

Steel welded with bronze rods may be tested by the same procedures employed in testing welds made with steel rods. Consideration should be given to the effects of relative areas of weld and base metal used in the test specimens.

Corrosion Testing of Stainless Steel

Three laboratory tests for corrosion of welded stainless steels have come into quite general use.

I. Boiling 65% Nitric Acid (Huey Test).[4]—This test is carried out by subjecting the welded samples to the action of boiling 65% HNO_3 for five 48-hr. periods. After each period the specimen is washed in water but not polished or scraped. It is then dried, weighed and immersed in fresh acid. Observe for each period:

1. Over-all inches penetration per month.
2. Appearance of weld and base metal (visual inspection).
3. Relative attack on the heat-affected zone.

The specimens are exposed to the boiling acid in a glass apparatus with suitable condenser to prevent loss of acid by evaporation. This test is used to determine metal quality and it also shows intergranular sensitivity by large weight losses.

II. Strauss Tests for Intergranular Corrosion.[5]—

1. Heat welded specimen 1 hr. at 650°C. (1200°F.).
2. Expose 72 hr. in boiling acidulated copper sulphate.*
3. Make free bend tests of weld to show whether the weld or adjoining base metal has been affected by intergranular corrosion. The specimen should give 20% bend elongation after this treatment or 180° bend according to ASTM Specification A240–40T.

III. Nitric-Hydrofluoric Acid Test for Intergranular Corrosion.—The specimen consisting of weld and base metal on both sides is immersed in a solution containing 3% hydrofluoric acid and 10% nitric acid heated to a temperature of 77°C. (170°F.) for a period of one hour. This treatment should not produce any visible evidence of corrosion attack and the specimen should withstand a bend through an angle of 180° without evidence of cracks.

The specimens for the boiling nitric acid test generally are finished all over, and for the intergranular corrosion tests and the nitric-hydrofluoric acid tests, they are always finished all over. A typical size of the test specimen is about 1 in. wide by at least 3 in. long. The length is sufficient to provide for testing the weld, the adjoining heated metal and metal unaffected by the heating.

* Solution: 47 ml. concentrated H_2SO_4 (sp. gr. 1.84) and 13 gm. crystalline copper sulphate ($CuSO_4$, $5H_2O$) per liter of water.

Corrosion Testing of Aluminum and Aluminum Alloys

When a specific use of welded aluminum or aluminum alloys is to be investigated, the conditions of service should be approached as closely as is possible. The following are representative examples:

I. Welded Drums or Tanks.—Prepare miniature welded drums and use them to store chemicals that are shipped in aluminum alloy drums. In the case of gasoline tanks, prepare small tanks and fill them with aviation gasoline and drainings from the sump of operating gasoline tanks; change weekly; provide air breather holes; secure motion of gasoline during period of test by attaching the sample tank to a truck that is in regular use. Corrosion in gasoline is greatly increased, if not controlled, by the presence of water in small amounts.

II. Atmospheric Tests.—Expose small panels containing welded specimens in an industrial atmosphere or seacoast atmosphere or intermittent salt spray tank[6] for periods of one to four years. Determine changes in properties by tensile tests of specimens taken transversely to the welds.

III. Sea Water Tests.—Expose panels of welded specimens either alternately or continuously immersed in sea water. The extent of the corrosion may be determined by microscopic examination, measurement of penetration or tensile test.

Corrosion Testing of Copper and Copper Alloys

The corroding medium in the type of test to be used for investigating the corrosion resistance of welded copper and copper alloys should be determined by the use that is to be made of the metal. Total immersion, alternate immersion or waterline tests may be used.[7] A 1% solution of sodium chloride is frequently used for corrosion tests of copper and copper alloys. The temperature of the solution is generally held at 60°C. (140°F.), and the time of testing, 30 days. If a stronger attack is desired, a 3% solution may be used. The attack is usually recorded in milligrams per square decimeter per day.

Sea water is sometimes used as a corroding agent. It is usual to subject thin strips of the metal to the test and to determine their corrosion-resisting properties by means of the tension test, although there are instances in which data on penetration per unit of time are of greater value. The tension test reveals the effect of pitting and also it shows the extent of intercrystalline attack to which the brasses containing over 30% zinc are sometimes subjected.

Corrosion Tests of Nickel and Nickel Alloys

The following tests are used to evaluate the corrosion-resisting properties of welded nickel, Monel and Inconel.

I. A total immersion test in aerated 5% sulfuric acid at a temperature of 30°C. (86°F.) for a duration of from 20 to 50 hr. The specimen is moved in a circular path at a rate of 15 ft. per minute.

II. Total immersion test in aerated $3^1/_2$% sodium chloride solution at a temperature of 30°C. (86°F.) for 30 days.

Polished sections of welded joints may be etched readily to disclose the weld and parent metal structure by immersion for 5 to 10 seconds in the following etchants:

(*a*) *For Monel*—a cold solution of equal volume of water and concentrated nitric acid.

(*b*) *For Nickel*—cold concentrated nitric acid.

(*c*) *For Inconel*—warm aqua regia after first warming the specimen in hot water. If the weld does not etch readily, a small amount of cupric chloride may be added.

Deposited weld metal is etched more rapidly than wrought metal and great care must be exercised when the structures of both the weld and parent metal are to be developed in the same etching for examination at high magnifications. It may be preferable to etch lightly and examine the weld metal and then re-etch and examine the parent metal.

Welded Hastelloy B is tested by total immersion in a boiling 10% solution of hydrochloric acid, and Hastelloy C in wet chlorine gas at room temperature. These tests of Hastelloys serve as typical examples of tests made to show the corrosion-resisting properties of a metal in a corroding medium to which it is to be subjected in use.

Corrosion Testing of Combination of Any Base Metal or Weld Metal Produced by Any Welding Process

In choosing a metal for any given purpose and deciding on a procedure of welding, resistance to corrosion should be taken into consideration. If tests of corrosion resistance are to be made, the type of test that will establish the same causes of corrosion as would occur in service should be selected and the test should determine whether the materials at the joint are equal to the metals welded, in respect to resistance to corrosion under a particular condition or set of conditions. Again, as in the case of all the tests that have been enumerated above, factors that dominate corrosion must be properly controlled. Usually when laboratory tests are made the controlling factors should be approximately the same and should bear the same relation to each other as the factors to be encountered in service. By correlation of laboratory tests with field and service tests the relative effect of corrosion on weld and adjacent base metal can be established and the conditions under which laboratory tests will give reliable results can be determined. The results obtained in the testing may be used to show whether the metal as welded is suitable for the expected use, and to provide data that will serve as a guide in the choice of base metals, welding rods and welding processes.

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CHAPTER 34A

IMPACT RESISTANCE OF WELDED JOINTS*

Tensile Impact Tests, Notch Impact Tests, Results of Impact Tests of Welds, Carbon Content, Low Alloy Steels, Austenitic Steels, Nitrogen (and Oxygen), Annealing, Welding Procedure, Non-Ferrous Welds, Flame Cutting, Welds at Low and Elevated Temperatures.

Introduction

SINCE welds, like other structural elements, often must withstand impact or suddenly applied loads, it is natural that impact tests of welds are much used. However, for low speeds, such as are used in Charpy and Izod tests, the effect of "suddenness"—speed of application—is not great.

In several European countries impact tests of welded specimens are required by codes and specifications. This requirement is quite limited as yet in the United States.

Although nearly all these specifications require a notched-bar specimen in impact bending, there are considerable variations among the specifications in two principal respects:

1. Type of specimen, Izod or Charpy (Mesnager).
2. Specimens prepared from an actual welded joint or from all-weld-metal.

Since it appears unlikely that an internationally standardized notch impact specimen even for unwelded metal will be adopted for some time, the existing differences between specifications may be expected to remain for the time being.

Tensile Impact Tests

The desirability for testing all zones of a welded joint in impact has led to the use of the tensile impact test for welds. The impact test measures the energy required to break a specimen, and not the stress. The resistance of an unnotched specimen to impact—or any energy load—depends on the method of loading and the volume of metal withstanding the blow. The resistance of a notched specimen depends on the shape and size of the notch

* Prepared by a committee consisting of W. Spraragen, Welding Research Committee, *Chairman;* G. E. Claussen, Machlett Lab., Inc.; H. F. Moore, University of Illinois. Specific test results reported in this chapter taken from Reviews of the Literature published in April 1936 and Sept. 1938 issues of THE WELDING JOURNAL.

and on what may be called the "notch sensitivity" of the metal. Up to the present the tensile impact test has been applied to welds only at the relatively low velocities available in pendulum machines.

The Netherlands Welding Standards specify an all-weld-metal tensile impact test for qualification of welding rods for steel bridges. The threaded specimen is 0.35 in. diameter, 2.36 in. parallel section and must yield 80 mkg./cm.^{2} (360 ft.-lb. total) fracture energy with 26% elongation in 2.36 in., 40% reduction of area when tested in a 540 ft.-lb. pendulum machine. Under some circumstances a "Charpy tensile bar" is included in the U. S. Navy procedure approval test plates.

I—NOTCH IMPACT TESTS

The variation of notch impact value with the dimensions of specimens is much more complex than the simple beam formula would lead us to expect. Although it is well known that for a fixed form of notch and fixed total depth of specimen the impact value is roughly proportional to depth back of notch in brittle materials and to the square of the depth in tough materials, the value usually lies between these two limits.

The Izod test does two things: (1) for comparatively brittle materials it gives a guide to the resistance to failure at a discontinuity; (2) it gives a guide to the resistance of a material during extension of a crack. This is probably true to some extent of the Charpy test as well. The Izod test is particularly important in detecting overheated structure in medium carbon steels, and revealing laminations and improper heat treatment.

Different notch impact machines of the same type may yield different impact results on identical specimens if the mass of the pendulums is different.

Location of Notch

The notch has also been located variously with respect to center line of plate or seam; e.g., at the transition between parent metal and weld, in the overheated zone.

Generally the Izod value of all-weld-metal appears to be about 50% greater when the notch is parallel to the direction of deposition than when it is perpendicular. The notched specimen is particularly useful for detecting the presence of embrittling metallographic constituents, such as nitrides, that take form during aging or in slow cooling after annealing, and for locating the brittle zone; it does not reflect the tensile properties of weld or parent metal.

The unnotched specimen may give lower impact values than the notched if the notch extends beyond the depth of a coarsely crystallized zone. Primarily, the unnotched specimen gives information about the quality of surface and junction zone, as well as about the degree of penetration.

There are still those who are skeptical about welding and regard the heat-affected zone as necessarily brittle in any steel. Tests have shown the zone to have ample low-temperature Charpy value even in base metal that is brittle in the Charpy test at low temperatures. Exhaustive Izod tests

on as-welded and annealed joints in mild steel and in cast steels with 0.10 to 0.30 C showed that the heat-affected zone was always superior to base metal.

The heat-affected zone in stress-relieved (1200°F.) arc welds in normalized (1500°F.) plates $1^3/_8$ in. thick containing 0.25 C, $2^1/_4$ Ni had a Charpy value equal to or higher than that of the base metal.

Standard Weld Tests (See Figs. 1 to 4)

The French Welding Institute's standard tests for filler metal have been extended to include both oxyacetylene and covered electrodes. A German Tentative Standard Method for Notch Testing of Butt Welds (DVM A122, April 1936) stresses the importance of placing the notch in the fusion zone. The new German Boiler Code specifies the DVMR specimen for plate less than 0.47 in. thick and the VGB specimen for thicker plate. The Mesnager specimen with notch in side of weld is specified in the Czechoslovakian Standards (CSN 1120). The Portuguese Navy requires minimum Charpy

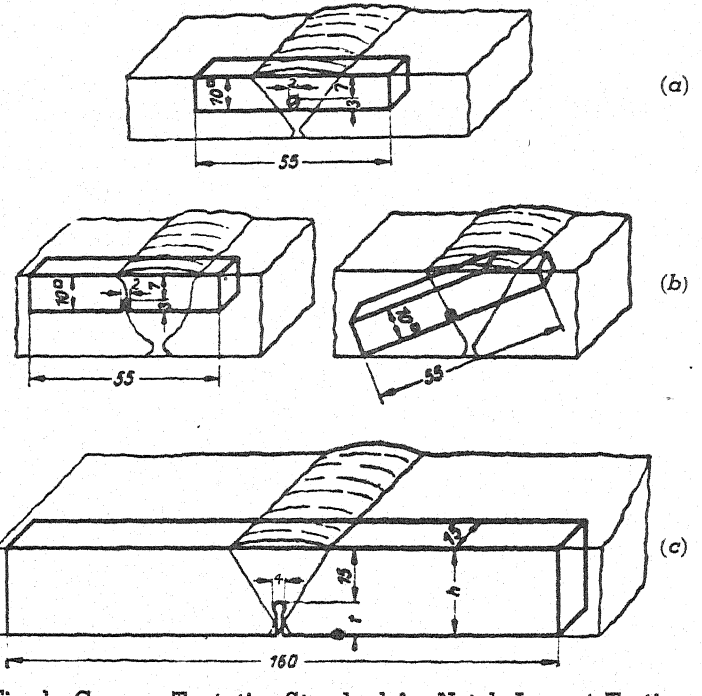


Fig. 1—German Tentative Standard for Notch Impact Testing Welded Joints (DVM A122)

(*a*) The usual location of the DVMR specimen with notch in root.

(*b*) For testing the junction zone between weld and base metal the surface perpendicular to the weld is ground and etched so that the notch may be accurately placed. If necessary and possible, the specimen may be cut at an angle to the surface.

(*c*) VGB specimen which may be used for thick material. t = depth of notch, h = plate thickness. Dimensions in millimeters.

values for welds of high and low strength. The Italian Standard for Gas and Arc Welding in Naval Construction requires that the average of four Mesnager specimens from a V butt weld attain 5 mkg./cm.^{2} In this country the A.S.M.E. Rules for Containers for Gases and Liquids at Sub-Zero Temperatures down to −150°F. require a Charpy or Izod specimen. A Charpy specimen (2 mm. drilled hole, A.S.M.) is included in the procedure approval test plates by the Navy for welding carbon-molybdenum and related steels. The notch is placed in weld metal, base metal and fusion line on both sides of the plate. The American Bureau of Shipping requires an Izod test specimen identical with Lloyds for qualifying weld-metal deposited by a new procedure.

Correlations with Other Tests

In order to determine what properties the weld impact test reveals, several attempts have been made to correlate the impact value of welds or

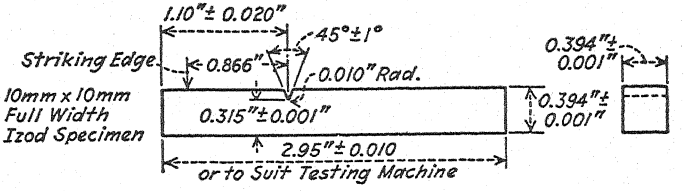


Fig. 2—Izod Impact Test Specimen

KEYHOLE NOTCH SPECIMENS

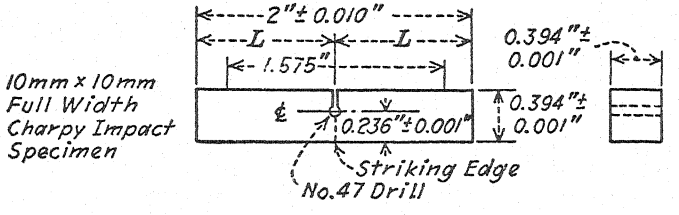


Fig. 3—Charpy Impact Test Specimen

EQUIVALENT NOTCH SPECIMENS

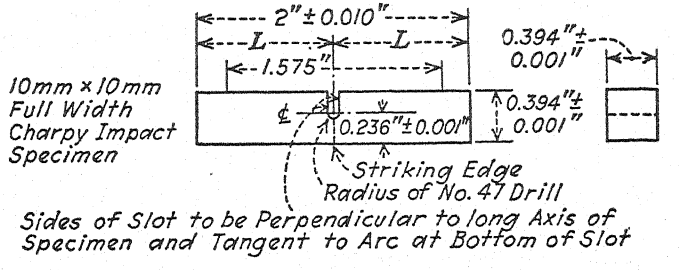


Fig. 4—Charpy Impact Test Specimen

weld deposits with the results of tensile, bend, hardness, fatigue, X-ray and service tests on identical materials. As in unwelded material, there appears to be no relation between yield point, tensile strength, yield ratio, energy absorption and hardness, and the results of impact tests. Between impact value and elongation, there is proportionality in general but the relation is by no means exact and sometimes fails to hold.

The tests of Petrenko and others indicate that there is a fair correlation between the energy shown by an impact test and the energy measured by the area under a load-deflection diagram of a static test of a similar specimen.

II—RESULTS OF IMPACT TESTS OF WELDS

Carbon Content

As the carbon content of weld metal increases, the notch impact value decreases. The DVMR value (notch in root) of welds made with heavy covered electrodes decreased from 12.4 to 5.6 mkg./cm.^{2} as the carbon content of base metal increased from 0.11 to 0.68%. Although the weld metal was not analyzed, doubtless it picked up carbon to an extent depending on base metal. The DVMR value of base metal decreased from 17.0 to 5.3 mkg./cm.^{2} in the same carbon range and oxyacetylene welds made with an alloy steel rod decreased from 9.8 to 2.0 mkg./cm.^{2} The impact value of welds rapidly decreased as the carbon content increased up to 0.3% but decreased much less rapidly thereafter up to 0.7%. An increase in carbon content of base metal also increases the ability of the steel to harden and become brittle in the heat-affected zone.

Using Mesnager specimens, one investigator found that laying one bead of an electrode at 180 amp. 7 in. per minute on 0.19 and 0.67 C plates 0.59 in. thick, reduced the impact values from 25 to 16 mkg./cm.^{2} and from 11 to zero mkg./cm.^{2}, respectively; in contrast he discovered that depositing four beads did not appreciably change the impact values of either 0.19 or 0.67 C plates. All notches in the welded specimens were parallel to and in the heat affected zones.

The weld and heat-affected zone in arc-welded cast steels containing 0.10–0.30 C, 0.4–0.5 Mn, 0.2–0.3 Si had higher Izod value than the unwelded casting. Stress relief heat treatment at 1200°F. and annealing at 1650°F. were always beneficial, the Izod value being increased as much as 15 ft.-lb. in most instances.

Oxyacetylene welds were made in steels with less than 0.10 C up to 0.33–0.37 C, 0.39–0.59 in. thick. Notch impact tests with the DVMR specimen indicated that the notch impact value as-welded depended on the quality of the rod, not on the carbon content of base metal. In all welds a reverse layer in the root was beneficial. Forging and peening also increased the notch impact value, particularly with low-grade rods.

Regardless of location of notch the impact value in most of the rail joints in arc and gas welds was higher than, and in the worst case only slightly lower than, the unwelded rail. There was no relation between notch impact value and ductility in the static tensile test.

Low Alloy Steels

In the Low Alloy Steel Chapter 18 on the properties of gas and arc-welded steels a great many determinations of Charpy value are given. The values range from 20 to 65-ft.-lb. It is impossible to summarize the results of all the low alloy steel tests. The reader interested in some special alloy steel or heat treatment is referred to the Low Alloy Steel chapter. Suffice it to say that many of these alloy steels and welds therein are particularly suited to withstand severe impact stresses.

Austenitic Steels

Austenitic filler metal is sometimes used for welding mild steel. Welds made with a mineral covered electrode containing 25 Cr, 12 Ni in aluminum treated S.A.E. X1020 had 70 ft.-lb. Izod at +70°F., 60 ft.-lb. at −184°F. Heat treatment (2 hr. 1100°F., furnace cool, or ½ hr. 1560°F. air cool) had no effect on different grades of austenitic weld metal. The DVMR value of welds made with 18–8 electrodes in plain carbon steels with 0.11 to 0.68 C was 13 to 15 mkg./cm.^{2} independent of base metal.

Nitrogen (and Oxygen)

Perhaps the greatest utility of the impact test for welds lies in its infallible detection in mild or alloy steels of constituents, such as nitrides, carbides or oxides, that have been in some way deposited in a damaging form within the metal.

The impact test has been of most service to the welding industry in demonstrating the benefits to be derived from effectively coated welding electrodes. Tests by a large number of investigators conclusively demonstrate the superior impact resistance of welds made with heavily coated electrodes of the shielded-arc type. The advance in Charpy values from 5 ft.-lb. with bare wire in 1920 to 30 ft.-lb. easily obtained at present with any good quality electrode in mild steel (Charpy 30 ft.-lb.) has been rapid and continuous. Unannealed gas welds generally have not more than 80% of the impact value of the parent metal, carbon arc welds (unprotected) approximately 20 to 40%. But values as high as 100% have been reported in heat-treated, automatic carbon-arc welds made in hydrogen.

Annealing

It was found that the impact value of arc welds prepared with bare or ineffectively coated electrodes was invariably decreased by 10 to 50% by annealing at about 1550–1700°F., whereas gas welds were improved by such treatment. Welds containing over 0.025 to 0.05% nitrogen or oxygen, introduced by bare or improperly coated electrodes, will display this peculiar effect, which may be ascribed to precipitation of oxides or acicular nitrides during slow cooling after annealing and which is not usually found after rapid cooling as in normalizing.

The normalizing effect of the upper layers on the lower layers of bare wire welds is detrimental to impact properties. In gas-free welds the impact value after annealing is dependent on temperature and hence on grain size. Annealing temperatures above 1650°F. coarsen the grain size in plate and

weld in mild steel and, therefore, lower the impact resistance. In gas-free high-strength welds, such as shielded arc welds, annealing just above Ac_3 may raise the impact value at 70°F. by 30%. One investigator found an Izod value of 3 ft.-lb. in the top run of a weld having 25 ft.-lb. in the lower layers.

In tests of 70° V butt welds made with blue asbestos covered electrodes in 1/2-in. mild steel plates, the Izod values were 35 to 80 ft.-lb. at +212°F., 15 to 25 ft.-lb. at 930°F. Both annealing and normalizing improved the Izod value 20% at +212°F., but did not change the transition temperature, or the Izod value at 930°F. The Izod value of normalized welds was unchanged by heating nearly 4 months at 480 or 840°F. with or without an applied tensile stress of 12,000 lb./in.^{2} The specimens were tested within 24 hr. of removal from the furnace. The Izod value at +70°F. dropped from 25 to 10 ft.-lb. after 45 days at room temperature following a water quench from 1200°F. The weld contained 0.06 C, 0.65 Mn, 0.066 N.

In tests of 70° V oxyacetylene welds in mild steel (tensile strength = 68,000 lb./in.^{2}) 0.59-in. thick, normalizing 20 min. at 1650°F. raised the DVMR and VGB values from 6 to 14 mkg./cm.^{2} (Fig. 1).

Welding Procedure

Peening and also forging of a finished weld are beneficial to impact value; increases of 10 to 100% have been reported. As plate thickness is increased from 3/8 to 3/4 in. the impact value of all types of welds tends to decrease in comparison with parent metal; the increase in impact value produced by hot forging after welding is greater in the thinner plate. The effect of current strength on impact value is relatively small although unusually high or low current lowers the impact value. The effect on impact resistance of a.c. as compared to d.c., of polarity and of arc length have also received attention but no effect of any magnitude was discovered. Within wide limits the quality of a flame cut bevel is without effect on the impact value of the joint. Backhand welding, because it gives rise to less severe overheating, is preferable to forehand from the standpoint of impact resistance of welds in steel.

Non-Ferrous Welds

Oxyacetylene welds in soft and hard-rolled aluminum (99.5% purity, 0.39 and 0.79 in. thick) made with aluminum rods of commercial purity had about one-half as high notch impact value (DVMR as well as VGB) as unwelded base metal. Cold hammering improved the notch impact value 1 to 4 mkg./cm.^{2}, and hot hammering raised the value to that of unwelded base metal.

Flame Cutting

The notch impact value of flame-cut surfaces has been determined by three investigators who agree that, for the steels tested and with the specimens employed, flame cutting does not have an adverse effect. The steels were: 1/2-in. plate containing 0.24 C and 0.46 Mn, 3/4-in. plate containing 0.10 C, 0.44 Mn, or 0.18 C, 0.47 Mn; 3/8-in. plate containing 0.12 C, 1.0 Mn, 0.6 Si, with either 0.3 Cu or 0.4 Cu and 0.1 Mo.

Welds at Low and Elevated Temperatures

Tensile impact tests of machined resistance butt and atomic hydrogen welds in steel containing 0.25 C showed that the welds had about the same ductility but 20% lower fracture energy than base metal at all temperatures. Impact energy and ductility were about 20% lower at −112°F. than at +70°F. with unexplained variations at intermediate temperatures. Bronze-welded joints had one-half the fracture energy and ductility of unwelded 0.25 C steel. Had the bronze the same yield and tensile strengths as the steel (say, 70,000 lb./in.^{2}, which is not difficult to attain with fluxes and rods now available), the deformation probably would not have been restricted to the relatively small proportion of bronze in the specimen, and the tensile impact value would have been higher. Oxyacetylene and arc-welded 18–8 had 50% lower fracture energy than unwelded 18–8 but 50% higher than plain carbon steel. The fracture energy was a little higher at −112°F. than at +70°F. with no difference in ductility. All fractures were fibrous at +70°F. and −112°F. The relation between static and impact tensile results at +70 to −112°F. was not at all close.

Welded 3½ Ni, 0.20 C steel had nearly the same tensile fracture energy at −100°F. as at +70°F. On the other hand, welded 3½ Ni, 0.35 C steel at −50°F. had only 10% of the room-temperature fracture energy. Less pronounced decreases were found with welded plain carbon and 2% Ni steels.

Welds made with mineral or combustible covered electrodes in aluminum-treated S.A.E. ×1020, ½ in. thick had Izod values of 45 to 76 ft.-lb. at +20°C., 15 to 50 ft.-lb. at −108°F. and 4 to 31 ft.-lb. at −184°F. With notch in heat affected zone the Izod was 80 ft.-lb. at −108°F. and 15 to 90 ft.-lb. at −184°F. Obviously the treatment with aluminum was beneficial to base metal. However, in plate 1½ in. thick the heat affected zone had only 3 to 10 ft.-lb. at −184°F. Stress relief heat treatment at 1200°F. slightly raised the Izod of heat affected zone at +70°F. and −58°F. but had no effect at −184°F. or on the weld. Normalizing at 1650°F. was not advantageous.

Stress-relieved two-pass and three-pass d.c. arc weld metal (1.6 Ni, 0.10 C) had 36 ft.-lb. Charpy at 70°F. and 22 ft.-lb. at −76°F., which was the same as fine grained rolled 0.09 C steel perpendicular to the direction of rolling or slightly below rolled 0.25 C, 2.4 Ni steel parallel to the direction of rolling. The heat-affected zone in base metal (2.33 Ni, 0.45 Mn, 0.14 C) had the same Charpy value (36 ft.-lb.) at −76°F. as unwelded base metal, whether or not stress relieved. Stress relief heat treatment raised the Charpy value of weld metal only 4 ft.-lb. at −76°F.

Investigations show that the high and low-temperature impact characteristics of good welds are practically identical with those of parent metal. A minimum in impact value is usually found at 750–1020°F. for welds in mild steel; for tough welds the minimum value is usually about 50% of the impact value at 70°F.

WELDED STRUCTURES

In general, welded structures of all sorts can be relied upon for excellent resistance to impact in service. By impact in service is meant either the

repeated hammer blow received, say, by a welded rail joint from passing locomotives or the sudden blow of unusual intensity under which the weld must hold to prevent widespread damage. In welded structures a considerable portion of the energy of impact may be absorbed by the elastic deformation of parts close to the weld.

CHAPTER 34B

FATIGUE TESTING AND PROPERTIES OF WELDED JOINTS*

Nature and Significance of Fatigue Failure, Stress Raisers, Definitions, Fatigue Machines and Specimens, Fatigue Strength of Joints, Influence of Mechanical Treatment, Defects in Welds, Alloying Elements, Fatigue of Non-Ferrous Metals, Fatigue Tests of Pressure Vessels and Full-Size Structural Members, Effect of Period of Rest, Riveted vs. Welded Joints in Low Alloy Steels, Fatigue Strength of Machine Parts, Railroad Rails.

1. NATURE AND SIGNIFICANCE OF FATIGUE FAILURE

AT the beginning of this chapter a brief statement of the character of static, impact and fatigue failures seems in order. Static failure may be due either to permanent distortion or fracture. In either event, it depends, except for very brittle metals, upon the average strength and ductility of a considerable volume of metal. Under static load or load repeated a few times, localized plastic action or even a minute localized fracture (crack) rarely causes appreciable structural damage.

Under relatively low speeds of loading—say speeds up to the fastest speed applied in a testing machine test—"impact" may, without serious error, be considered as producing the same *type* of deformation and of stress distribution as static loading. As the rapidity of loading increases, the type of deformation and of stress distribution is modified by the inertia of the parts deformed. For example, under rapid loading a long-span beam supported without end restraint acts as if the ends were partially restrained, and a slight negative bending moment is produced at the supports by the inertia of the beam itself.

In a very long member, such as the drill rod in an oil well, an appreciable time is required for the wave of stress (traveling at a speed of 17,000 ft. per sec. in steel) to traverse the whole length of the member and be reflected back again, so that the upper end of the rod may be in tension while at the same instant the lower end is in compression. In a part subject to repeated cycles of load, resonance may be built up by the transmission and reflection of waves of stress, with consequent crests and nodes of stress.

* Prepared by a committee consisting of H. F. Moore, Research Professor of Engineering Materials, University of Illinois, *Chairman;* Chas. H. Jennings, Chemical and Metallurgical Department, Westinghouse Research Laboratories; and W. M. Wilson, Research Professor of Structural Engineering, University of Illinois.

The particular frequencies of cycle of stress which cause such resonance are sometimes called "critical speed." In turbine disc wheels it is important that the disc be so designed that none of its frequencies of resonant lateral vibration synchronize with the speed of revolution of the shaft.

This whole matter of inertia stresses and vibrations in structural parts, and especially in machine parts, involves for its solution elaborate mathematical analysis, or experimental determination of critical speeds and inertia strains and stresses.

Recent studies by Mann at Watertown Arsenal, and by other experimenters, have raised the question whether for a metal there is a "critical" rate of strain, above which the toughness (energy required for fracture) of the metal sharply decreases, possibly on account of the fact that plastic deformation proceeds more slowly through a piece of metal than does the elastic deformation due to ordinary working stresses and fracture occurs before plastic action can be fully developed. However, data in this field are at present quite inadequate to justify the statement of any quantitative values for this diminution of toughness.

Fatigue is a spreading failure, originating at some localized region where there is a structural weakness or structural damage has occurred. Continued repetition of a sufficiently high load causes a minute crack to develop in that region of localized structural damage, and then to spread, until fracture of the structural part occurs. This means that under repeated loading, minute localized structural damage, which would be negligible under static loading, may be of vital importance.

Some welded joints occasionally contain minute flaws such as gas holes, inclusions or unfused areas, and they are more susceptible to fatigue failure than ordinary rolled structural steels. As a result, welded joints have had their most general application either on structural and machine parts which are subjected to steady loads, or on structures such as pressure vessels which are subjected to a comparatively small number of repetitions or cycles of stress. This means that welding has been used more in structural work than in the making of such parts as shafts for machines, which are subjected to millions of cycles of repeated stress. Dynamically loaded structures such as blowers, rotors, gears, etc., are satisfactorily welded, however, when properly designed.

The design of welded joints for pressure vessels and for structural members which are subjected to some repetition of stress, constitutes a fatigue problem somewhat different from that of a shaft. In the normal life of these structural parts or pressure vessels, there would occur a few thousand repetitions of stress rather than tens or hundreds of millions, and the limiting stress below which it would be reasonably certain that the part would stand, say, 200,000 cycles might be regarded as the fatigue limit for members of this intermediate class, rather than the fatigue limit for an indefinitely large number of cycles of stress.

Stress Raisers

The ordinary formulas of mechanics of materials have been developed mainly for the design of structural members subjected to static load, and they almost entirely neglect to consider localized stresses due to nonhomogeneity of material and sudden changes of cross-section in structural

parts. There are very many localized regions in structural parts where the stress is higher, sometimes much higher, than that computed by the ordinary formulas for strength of materials.

Any cause which produces a localized area of high stress is called a "stress raiser." Abrupt changes in section, notches, grooves, screw threads, surface irregularities and discontinuities, such as cracks, holes or inclusions, are stress raisers. There is a possibility that an abrupt change in the physical properties of a material, such as may occur at the junction of the weld metal and base metal when the two are of materially different compositions, acts as a stress raiser. The effect of a round hole in a plate, and of some other simple stress raisers have been determined by elaborate mathematical analysis and by studies of transparent models viewed by polarized light, but, because the *effect* of stress raisers on the fatigue strength of a specimen is a function of the physical properties of the material as well as of the geometrical shape of the stress raiser, these studies are of limited usefulness in predicting the value of the fatigue strength of a joint. However, they yield results "on the safe side," and are of real value in determining types of geometrical stress raisers to be avoided.

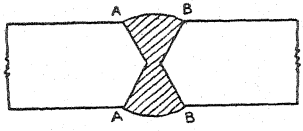


Fig. 1—Butt Weld in Structural Plate—High Stress Concentration at Edge of Reinforcement

A distinction should be made between the fatigue strength of weld metal and the fatigue strength of welded joints. The former is affected by the properties of the filler and base metals, and by such stress raisers as porosity, slag inclusions and surface imperfections. The latter is affected by all of the above and also by lack of fusion and by geometrical stress raisers incident to the design and fabrication of the joint. The latter are often more injurious than the former. Figure 1 shows a typical double-V butt weld in a plate. The abrupt change in section at the edge of the reinforcement constitutes a stress raiser that may overshadow the effect of imperfections in the weld. Tests of butt welds in $^{7}/_{8}$-in. plates (C = 0.23%; Mn = 0.47% and Si = 0.02%) showed that the fatigue strength (0 to tension, failure at 2,000,000 cycles) was 22,500 psi. in the as-welded condition, 28,400 psi. when the reinforcement was machined off, and 31,600 psi. for a plate without weld, the value given being the average of three tests in each instance. That is, eliminating the stress raiser due to the change in section at the edge of the reinforcement increased the fatigue strength of the joints 25 per cent to a value only 10 per cent less than the fatigue strength of a plate without weld.

The abrupt changes in section at the edges of transverse fillet welds, shown in Fig. 2, are also severe stress raisers that greatly impair the fatigue strength of the joint.

The fatigue strength of a joint consisting of plates connected wholly or partly with longitudinal fillet welds, shown in Fig. 3, is low, due to the fact that the stress is introduced into the plate along the edges and "piles up" at the end of the fillet, tending to cause fatigue failure of the outer plates at *A* and *A* or of the inner plates at *B* and *B*. This, being in addition to

the stress raising effect of the change in section, greatly reduces the fatigue strength of the joint. So great is this destructive effect that a joint designed for a longitudinal shearing stress of 20,000 psi. at the throat of the

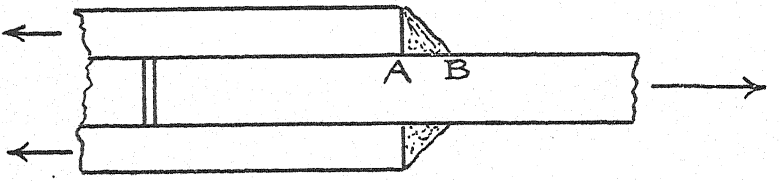


Fig. 2—Fillet Weld—High Stress Concentration at B

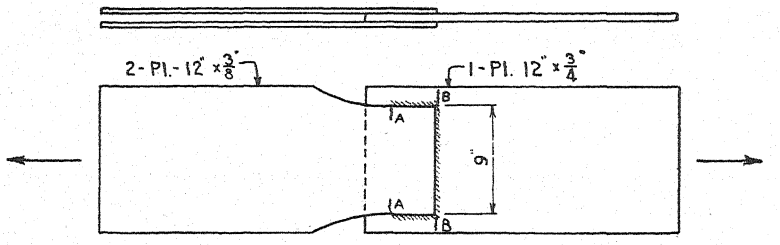


Fig. 3—Longitudinal Fillet Weld with High Stress Concentration at Ends of Fillet

fillet and a tensile stress of 10,000 psi. on a transverse section of the outside plates, failed in the plates, the weld remaining intact.

The destructive effect of the stress raisers in welded joints that are used to connect structural members is known to be very great and varies with the type of joint. However, there are not enough experimental data available to establish adequately the fatigue strength, except perhaps for the double-V weld in carbon steel plates. Moreover, it would seem that the necessary data can be obtained only by fatigue tests of full-size joints.

Definitions and Nomenclature

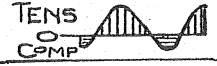
New developments in the study of fatigue of metals are taking place so frequently that anything like fixed standards of definitions and nomenclature have not been established. The following definitions are given for use in reading this section.

Repeated Stress.—A structural member or a machine part is subjected to repeated stress if, during its regular service, the stress fluctuates because of vibration, change of load, change of temperature or other cause. Repeated stress is a general term and includes pulsating stress and reversed stress, which terms are defined later.

Fatigue of Metals.—When, under the influence of repeated stress, a crack starts and spreads in a structural member or machine part, "fatigue of

Table 1—Numerical Examples of "Range Ratio" and "Mean Stress" Nomenclature for Repeated Stress

In this table are given nine typical examples of the use of two systems of nomenclature for cycles of tensile and compressive stress. A similar tabulation could be made for cycles of shearing stress uni-directional and reversed. All values of stress are given in pounds per square inch.

Range of Stress Applied During Cycle	Diagram of Stress During Cycle	Range Ratio Nomenclature		Mean Stress Nomenclature	
		Range Ratio (r)	Maximum Stress	Mean (Steady) Stress (Ss)	Reversed (Alternating) Stress (Sa)
(1) Steady stress, 30,000 tension		+1.0	30,000 tens.	30,000 tens.	0
(2) Pulsating stress from 10,000 tens. to 25,000 tens.		+0.4	25,000 tens.	17,500 tens.	± 7,500
(3) Pulsating stress from zero to 20,000 tens.		0	20,000 tens.	10,000 tens.	±10,000
(4) Partly reversed stress from 5,000 comp. to 18,000 tens.		−0.278	18,000 tens.	6,500 tens.	±11,500
(5) Completely reversed stress from 13,000 tens. to 13,000 comp.		−1.0	13,000 tens. or comp.	0	±13,000
(6) Partly reversed stress from 6,000 tens. to 22,000 comp.		−0.273	22,000 comp.	8,000 comp.	±14,000
(7) Pulsating stress from zero to 24,000 comp.		0	24,000 comp.	12,000 comp.	±12,000
(8) Pulsating stress from 10,000 comp. to 20,000 comp.		+0.5	20,000 comp.	15,000 comp.	± 5,000
(9) Steady stress, 35,000 comp.		+1.0	35,000 comp.	35,000 comp.	0

metals" is in progress. "Progressive fracture" would be a better term than "fatigue of metals."

Pulsating Stress.—A stress varying between a maximum value and a minimum value, both stresses being in the same direction. The minimum value of a pulsating stress cycle may be zero as shown in Table 1 (3) and Table 1 (7), or some numerically larger value as shown in Table 1 (2) and Table 1 (8).

Reversed Stress.—A stress varying between a maximum value in one direction and a minimum value in the opposite direction, such as a cycle of stress in which the stress ranges from tension to compression. The numerical values of the maximum and the minimum stress may be the same, as shown in Table 1 (5), or different as shown in Table 1 (4) and Table 1 (6). When the maximum and minimum numerical values of stress are the same the term "alternating stress" or "completely reversed stress" is sometimes used.

Endurance Limit or Fatigue Limit.—The numerically largest repeated stress which, without causing fracture, may be applied to a given material either for an indefinitely large number of cycles or for a given number of cycles. If used without a qualifying adjective "endurance limit" usually means the limit for an indefinitely large number of cycles under completely reversed (alternating) stress. Figure 4 (*a*) shows the type of stress-cycle or *S-N* diagram most commonly found for metals. The diagram approaches a horizontal line as the number of cycles necessary for fracture increases, and the ordinate of this horizontal line is taken as the endurance limit for an indefinitely large number of cycles of stress. For some metals the *S-N* diagram does not approach a horizontal line. In such a case it is necessary to determine an endurance limit for a definite number of cycles of stress. Figure 4 (*b*) shows the determination of endurance limit for 200,000 cycles of stress (FL_B) and for 50,000,000 cycles of stress (FL_C).

While no system of quantitative nomenclature has become recognized as standard for repeated stress, two systems are in use in English-speaking countries. In the first system the nomenclature is based on *range ratio* (conveniently denoted by r). This is the ratio of the (numerically) smallest stress during a cycle to the (numerically) largest stress; r may be either $+$ (no reversal of stress) or $-$ (partial or complete reversal), and is never numerically greater than 1. To define a cycle of stress completely the numerical value of r together with the proper sign ($+$ or $-$) and the magnitude and kind of the largest stress in the cycle must be given. Examples of this nomenclature are given in Table 1. This system has proved convenient for machine designers and structural engineers, since for machines and structures under design the ratio of minimum to maximum load is frequently known.

The second system of nomenclature is based on the fact that any cycle of repeated stress may be regarded as made up of a mean steady stress, S_m, and an alternating (completely reversed) stress, S_a, superimposed on the steady stress. Examples of this nomenclature are given in Table 1 This system is convenient for use in the analysis of test data, and for plotting diagrams to show the effect of varying range of stress on the endurance limit of a metal.

Efficiency of a Welded Joint.—The efficiency of a welded joint is the ratio of the strength of the welded joint to the strength of the base metal; this

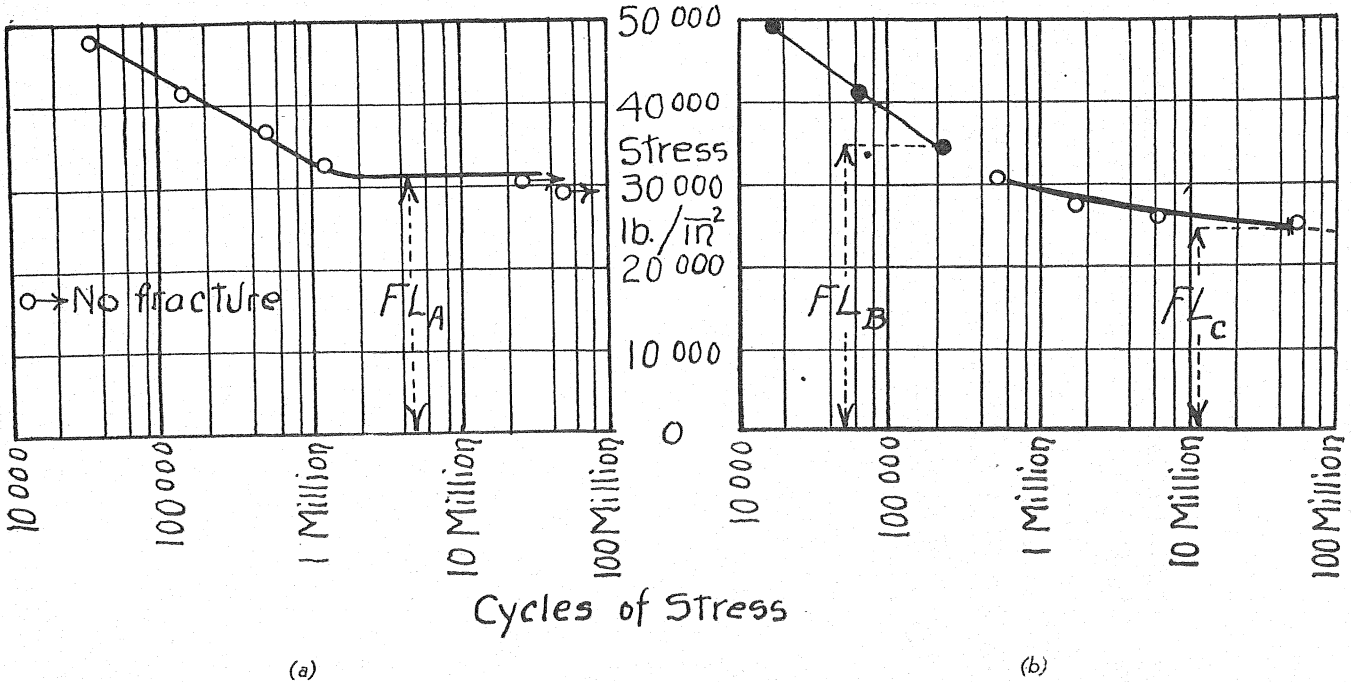


Fig. 4—S-N (Stress-Cycle) Diagrams for Fatigue Tests

FL_A—Endurance limit 32,000 psi., indefinitely large number of cycles of stress (S-N diagram becomes horizontal).
FL_B—Endurance limit 34,000 psi., 200,000 cycles of stress.
FL_C—Endurance limit 24,000 psi., 50,000,000 cycles of stress.

definition is similar to that for the efficiency of a riveted joint. The efficiency is expressed in per cent.*

II. FATIGUE TESTING MACHINES AND SPECIMENS FOR WELDED JOINTS

The fatigue strength of a welded joint depends upon the geometrical properties of the specimen as well as upon the physical properties of the material. Moreover, the fatigue failure of a welded joint frequently occurs in the base metal adjacent to the weld rather than in the weld itself. This is not necessarily due to metallurgical injury to the base metal, but may be due to geometrical stress raisers, which, in turn, depend on the details of the joint. For this reason two types of specimen are needed in the determination of the fatigue strength: (1) small machine and polished specimens as free as possible from geometrical stress raisers, designed and loaded in such a manner as to cause the maximum stress to occur at the junction of the weld and base metal; (2) specimens that are as large as it is feasible to test and that have the geometrical characteristics and surface finish of the joints that are to be used to connect structural members or machine parts.

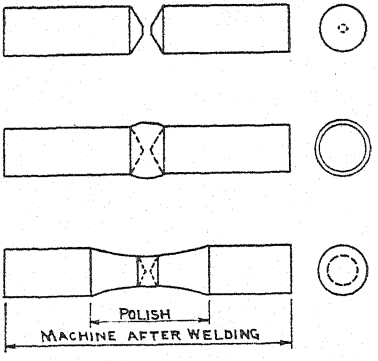


Fig. 5—Specimen for Determining Fatigue Strength of Weld and Joint

Specimens of the first type, those used to determine the fatigue properties of the weld metal, are usually of the form shown in Fig. 5. Specimens of this type can be tested either in flexure or by direct axial loads, and in the machines that have been developed for determining the fatigue strength of various metals.† There is, however, this difference. A specimen without a joint is fairly homogeneous and can be made quite small; specimens with a joint of the type shown in Fig. 5 may have porosity or inclusions in the weld, and these stress raisers will have a greater effect upon the fatigue strength of a small specimen than upon that of a large one. For

* By some writers this ratio, when applied to fatigue test results, is called the "weld endurance ratio." However, in the United States the term "endurance ratio" is rather commonly used to denote the ratio between endurance limit under reversed flexure and static tensile strength.

† A number of these machines are described in the A.S.T.M. Proceedings, *30*, Part I, p. 261, and in University of Illinois Engineering Experiment Station, *Circular No. 23*.

this reason, a specimen of larger diameter should be used for fatigue tests of a welded joint than for fatigue tests of a bar without a joint, even though the specimen is machined and polished and of simple geometrical outline.

Specimens used in tests to determine the fatigue strength of welded joints used to connect structural members and machine parts should, as pointed out above, be as large as it is feasible to test and should have the geometrical characteristics and surface finish of the prototype. The specimens used in most tests of this type have been: (1) plates connected with butt welds and subjected to an axial load; (2) channels connected to plates or a plate connected to other plates by either transverse or longitudinal fillet welds, or a combination of the two, subjected to a pulsating or reversed axial load; (3) welded joints connecting beams to columns subjected to a pulsating or reversed moment.

Figure 3, 6 and 7 show specimens typical of many that were tested in a comprehensive investigation of the fatigue strength of welded joints that has been sponsored by the Welding Research Committee of the Engineering Foundation.* A lever type of fatigue testing machine was used for

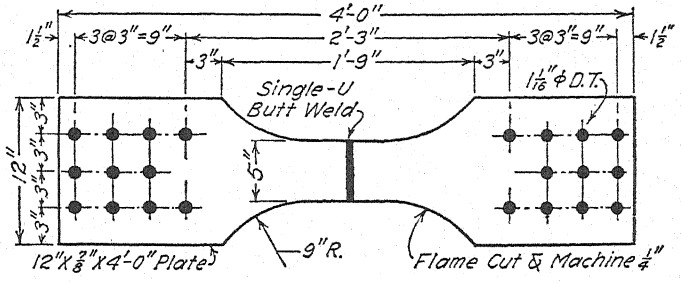


Fig. 6—Welded Joint Specimen for Testing Under Repeated Axial Stress

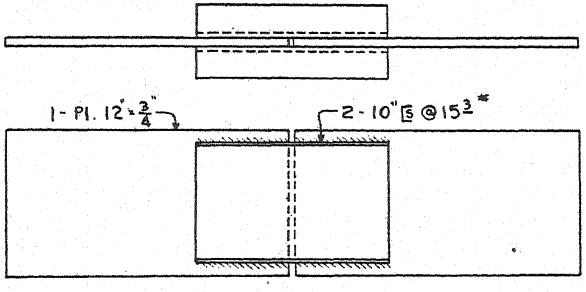


Fig. 7—Specimen for Determining Fatigue Strength of Joint with Longitudinal Fillet Weld Connecting Channels and Plates

* This is a part of the work of Committee F, Fatigue Committee (Structural), Industrial Research Committee, Jonathan Jones, Chairman. See University of Illinois Engineering Experiment Station, *Bulletin 327* for the results of the tests.

these tests which was capable of producing a cycle in which the load varied from a tension of 200,000 lb. to a compression of the same magnitudel. Moreover, either the maximum or minimum load could be adjusted independently of the other so as to obtain any desired stress cycle so long as neither the tension nor the compression exceeded 200,000 lb.

The characteristic features of this machine are:

1. A lever for multiplying the force.
2. An adjustable-throw crank for moving the outer end of the lever up and down the amount necessary to produce the desired stress in the specimen.
3. Three fulcrums or pivots, one to support the lever, one to connect the short end of the lever to the upper pulling head and the third to connect the lower pulling head to the frame of the machine.
4. Heads for attaching the specimen to the machine.
5. A dynamometer for measuring the force.
6. Power for rotating the crank.

Figure 8 is a schematic drawing of this machine. It consists of the specimen S, the pulling heads G' and G'', the lever L, the crank C, the dynamometer D and the pivots at the ends of the pulling heads and the lever support.

The critical feature of the machine is the pivots. They must be able to withstand many millions of applications of the large load, they must be compact and they must not produce appreciable moment in the specimen. A "rolling" pivot is used for this machine. Each consists of a segmental roller which is attached to the lever and fits closely between the horizontal faces of the bearing blocks, one above and the other below the segment. The parts in contact are hardened tool steel. When the specimen is in tension the segment supporting the lever rolls on the lower base, when it is in compression the segment rolls on the upper base. The line of contact is always directly above or below the center of the segment. This fulcrum is compact and produces no moment at the end of the specimen except that the line of contact moves slightly from one side of the center line of the head to the other side due to the angular motion of the lever. The outer end of the lever is 200 in. long and the radius of the segment is 5 in., so that if the outer end is 1 in. either above or below the horizontal position of the lever, the line of contact on the pulling head is 0.025 in. from the centerline of the head.

The lever-type machine with a capacity of 50,000 lb. has been made with plate fulcrums and also with roller bearings. The flexure of the plate fulcrum introduces a very small moment in the specimen and the friction of the roller bearing introduces a very small moment and, because the rotation of the bearing is so small, there is a tendency for the rollers and races to wear at the line of contact. Two machines of this type had the pins fitted into the fixed bearing just tight enough to prevent up-and-down motion but loose enough so they could be turned with a large wrench. The pins have been systematically turned by small amounts at frequent intervals so as to shift the position of the line of contact. The bearings of this machine are apparently in good condition after two years' service. Perhaps a better expedient would have been to have had roller bearings in both the lever and the fixed supports so that the pins would "float," and then provide a power drive to rotate the pins at a few revolutions per

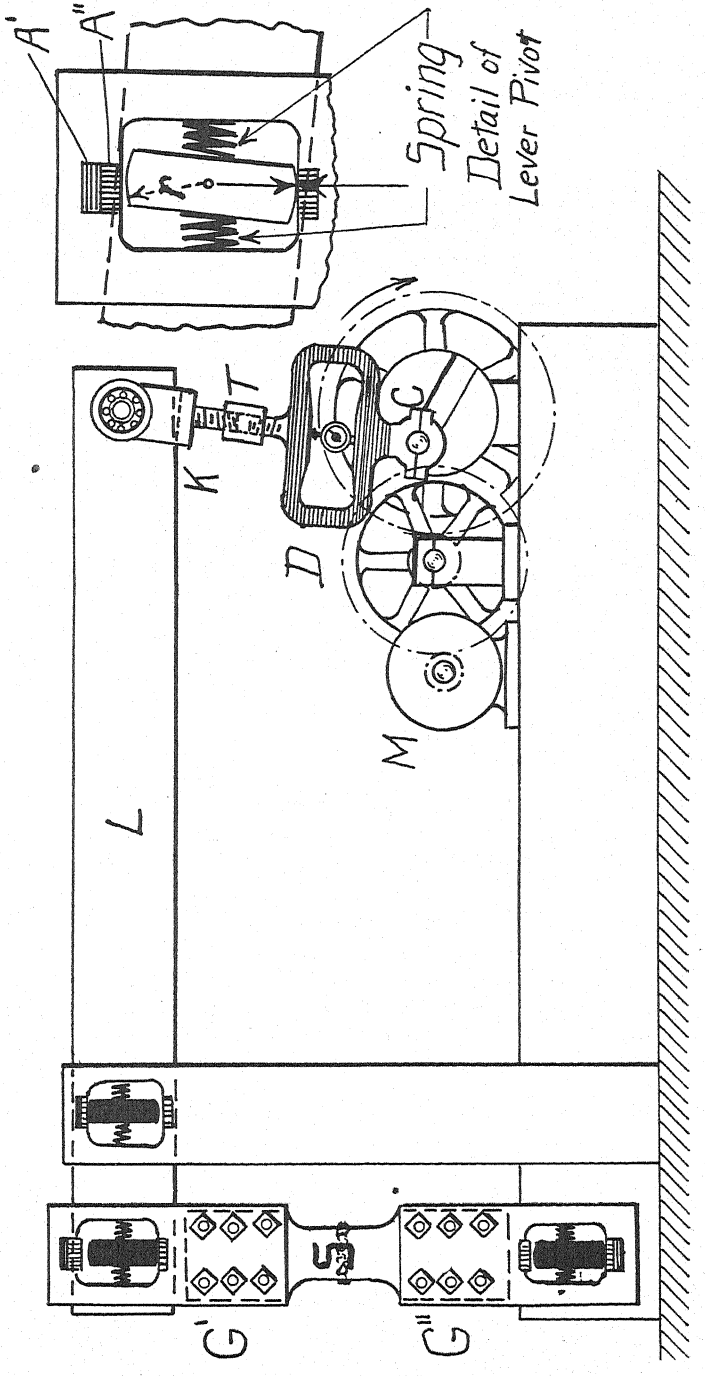


Fig. 8—The Wilson Fatigue Testing Machine

minute while the machine was operating, thus eliminating both the "friction of rest" of the roller bearings and the wear on the line contact.

Figure 9 shows in diagram a machine that was used to subject a beam-to-column joint to reversed and pulsating moments. It consists essentially of a variable-throw crank, a dynamometer and a mechanical drive. It was used successfully to test connections between 12-in. I-beams and 12-in. steel columns.

Figure 10 shows in diagram an arrangement for subjecting boiler drums or other pressure vessels to cycles of repeated hydraulic pressure. Steady

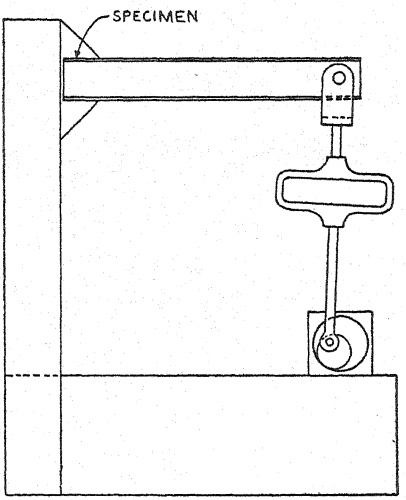


Fig. 9—Fatigue Testing Machine for Subjecting a Beam-to-Column Connection to Pulsating or Reversed Bending

pressure is furnished by a hydraulic accumulator, and water under pressure is alternately admitted to and allowed to escape from the vessel under test. This is accomplished by valves operated by a motor-driven series of levers. Such an apparatus has been used by the Babcock and Wilcox Co. with hydraulic pressure as high as 1570 psi. and at a speed of 15 cycles per minute.

Figure 11 shows in diagram a fatigue testing device developed by Dr. R. K. Bernhard, Pennsylvania State College, suitable for testing full-size structural members. It consists of four rotating discs on two parallel shafts. Each shaft is driven by a motor and the shafts are geared together so as to rotate in opposite directions at the same speed. To each disc is attached an eccentric mass. By the use of these eccentric masses placed at different distances from the center of the disc and by variation of the speed of rotation, a considerable variation in magnitude of load can be obtained. High speeds of rotation give increased loads and increased numbers of cycles of stress per minute. If the masses are attached as shown

in Fig. 11, the horizontal components of the centrifugal forces of the eccentric masses neutralize each other. The beam under test is subjected to cyclic loads varying from a maximum equal to (centrifugal forces of eccentric masses) + (weight of test apparatus) downward to a minimum equal to (centrifugal forces of eccentric masses) − (weight of test apparatus) upward.

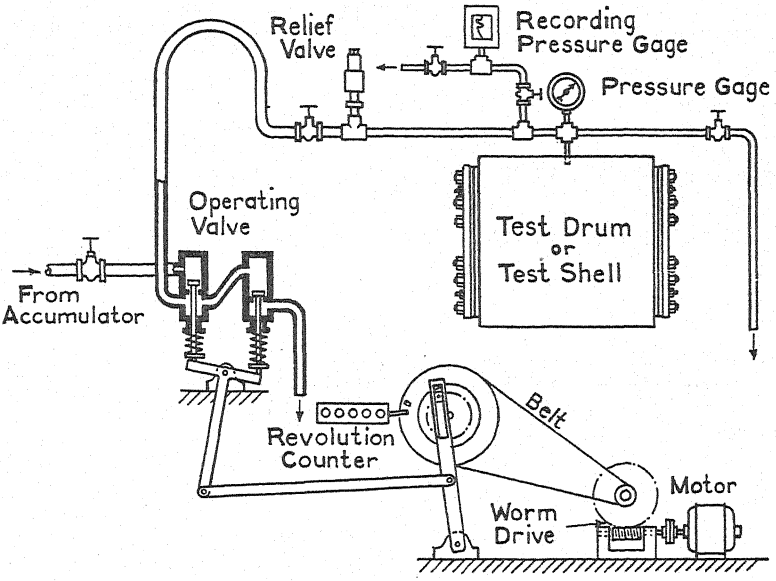


Fig. 10—Test Rig for Applying Repeated Cycles of Hydraulic Pressure to Pressure Vessels

III. FATIGUE STRENGTH OF SPECIMENS FROM WELDED JOINTS

Many of the data included in this section are taken from a summary of test results made by Spraragen and Claussen,* although other reported test results have been given also. Conclusions drawn from these data should be regarded as tentative.

Fatigue failure of a welded joint may occur in any one or a combination of several different ways:

(1) Failure in the deposited weld metal. The endurance limit in this case depends upon the welding process and procedure (method of welding, kind of electrode or filler metal, treatment, etc.), base metal and quality of the weld. Porosity, slag inclusions and poor fusion lower the endurance limits through their effects as stress raisers. Although it is known that these defects lower

* Spraragen, Wm., and Claussen, G. E., "Fatigue Tests of Welded Joints—A Review of the Literature Oct. 1, 1936," a publication by the Welding Research Committee of the Engineering Foundation, New York, also published in the Welding Research Supplement of *The Welding Journal*, 16, No. 1, January 1937. In this publication will be found information as to the experimenters, old methods and materials, apparatus and test methods used, and a bibliography of the source articles and books.

the endurance limits, there is virtually no quantitative experimental evidence available.

(2) Failure in the line of fusion. In this case failure is usually the result of poor fusion, lack of penetration or some other cause such as microscopic cracks which produce stress raisers.

(3) Failure in the heat-affected area. The heat cycle accompanying welding produces a structural change immediately adjacent to the weld deposit. The nature of this structural change is a function of the welding process and procedure and the analysis of the base metal. In some cases the heat-affected area will have a higher endurance limit than the original base metal, while in other cases it will have a lower endurance limit.

(4) Failure at the edge of the weld. Stress raisers at the edges of the weld caused by the joint design, weld contour and undercut frequently cause fatigue fractures to occur through the base metal at these points. Failures of this type are generally the combined result of the effects produced by the stress raisers and the heat-affected area.

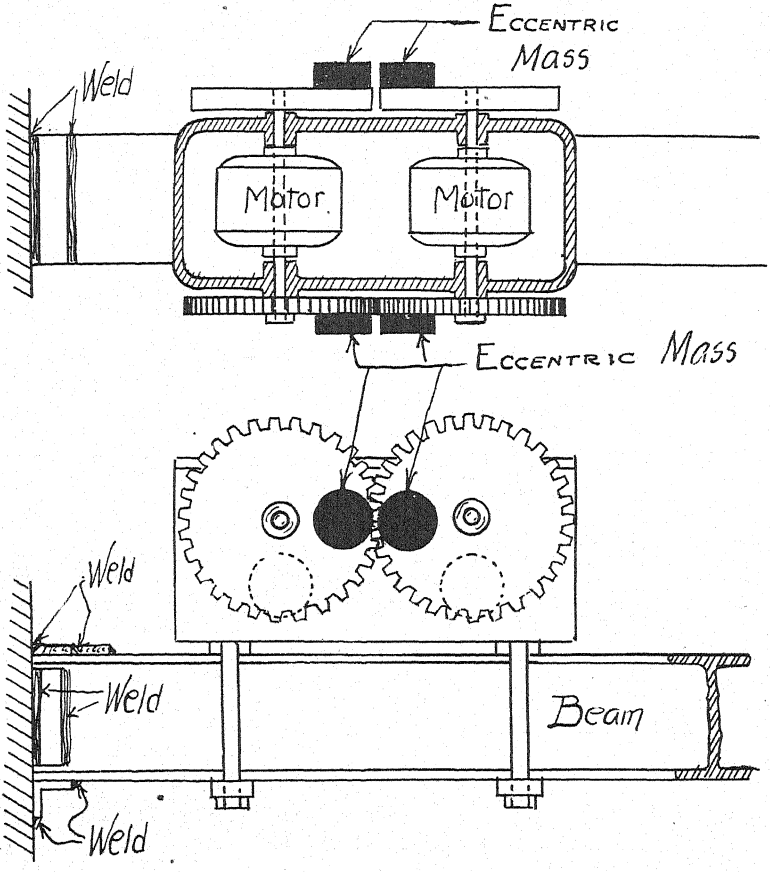


Fig. 11—Oscillator Machine for Applying Cycles of Stress to Welded Structural Parts

The published data on fatigue properties of welded joints show a wide scatter in the endurance limits obtained. This scatter is largely the result of the welding procedures used in making the joints, the quality of the welds and the type and location of the defects causing the failures. In analyzing fatigue data, it is therefore important that as much as possible be known about the welding process, welding procedure, weld quality and types of failure.

Endurance Limits of Welds in Low-Carbon Steel (Arc and Gas)

The results of tests of rotating-beam specimens carried to a maximum of at least 10,000,000 cycles of stress give endurance limits ranging from 25,600 to 31,000 psi. for welds made with covered electrodes. Endurance limit values of 16,000 psi. for bare electrode welds and of 30,000 psi. for covered electrode welds are commonly assumed values. These values represent a weld efficiency of 60 to 80%, if ordinary mild steel is the base metal.

The endurance limits for specimens from gas welds generally lie between the above limits for metal arc welds, and range from about 15,000 psi. to 26,000 psi. for welds with mild steel base metal.

Axial (tensile-compressive) fatigue tests frequently give low endurance limits. The stress distribution across the specimen is rarely uniform, and this may, in part, explain the low values. Low values occur particularly when wide specimens are used, especially with specimens held in wedge grips. Values of axial fatigue tests have been reported as low as 70% of the value for rotating-beam tests. One laboratory reported a rotating-beam (complete reversal) endurance limit 1.4 times the endurance limit for an axial tensile stress varying from nearly zero to a maximum. Since it has nearly always been found that the endurance limit in pulsating tension is higher than that in reversed bending, the 1.4 ratio for this case is regarded as due to special test conditions.

For axial (tensile-compressive) fatigue tests of small specimens some tests show less difference between the strength of welds made with bare electrodes and of welds made with covered electrodes than is the case for flexure tests. This may be due to the fact that reversed-bending fatigue tests emphasize the effect of surface defects, while in direct tension-compression tests, with stress nearly uniform over the cross-section, surface defects are less important.

Test results of torsional fatigue tests (shearing stress) of specimens from joints show about 25% lower efficiency than that shown in tension-compression or in rotating-beam fatigue tests. The endurance limit of metals has been found by many experimenters to be lower in torsion than in flexure or axial-stress tests.

Some test data indicate that the scarf angle affects the fatigue strength only as it affects penetration. It is recommended that the scarf angle be as small as possible consistent with good fusion.

In some tests of specimens single-V welds have shown the highest endurance limits in the as-welded condition, while double-V welds have shown the highest endurance if stress-relieved.

Fatigue tests of specimens from welds made with different sizes of electrodes show variation in the fatigue strength of the weld which can probably be ascribed to variations in workmanship. A reverse run (re-welding the root) raised the endurance limit in pulsating tensile tests and in reverse bending tests 10 to 20%. The reverse run is helpful because it eliminates almost entirely the stress-raising effect of the usual notch at the root of the bevel, and not because it refines the grain structure.

Miscellaneous Test Results

The endurance limit of a sound deposit of weld metal is about the same as that of rolled steel of the same chemical composition, except when the weld metal is deposited with bare electrodes. The presence of porosity or inclusions in a weld metal deposit may lower the endurance limit 15% or more.

Preliminary results of fatigue tests of welds at elevated temperatures indicate that the endurance limit of welds differs but slightly from that of unwelded mild steel.

The fatigue properties of atomic hydrogen welds are about the same as those of gas welds and arc welds. Resistance welds, however, have shown remarkably high endurance limits, especially in fatigue tests in corrosive media. The torsional fatigue limit for flash welds in mild steel is about the same as that for the base metal. Pulsating tensile ("*r*" very small) endurance limits for carbon-arc welds range from 14,000 to 21,500 psi., the value depending upon the technique of the welding operator. The endurance limit of a brazed joint in mild steel $^3/_4$ by $^3/_8$-in. cross-section was found to be 20,000 psi. when tested in reverse bending.

Influence of Mechanical Treatment

Peening.—One investigator found the unmachined all-weld metal deposited by bare electrodes had an endurance limit of 18,000 psi. in rotating-beam (cantilever) tests. Peening each layer of deposited metal raised the endurance limit to 20,000 psi.

Hot Forging.—Hot forging raises the endurance limit but, because of grain growth, the increase due to forging at temperatures of about 1200°C. (2192°F.) is not great. Hot forging increases the endurance limit of back-hand gas welds by 20%; of fore-hand welds by only 10 per cent. Forging of welds in mild and alloy steels made with coated or cored electrodes (0.07% C, 0.65 to 2.8% Mn) increases the endurance limit from 75 to 100%.

Machining.—Experiments show that for medium and high quality arc welds, butt or fillet, in structural steel, intelligent removal by machining of undercutting and other surface notches or reinforcement raises the endurance limit about 25%. For welds of poor quality having many inclusions, machining is of no appreciable advantage. One investigator reports 40 per cent increase in pulsating endurance limit of parallel shear fillet welds the inner ends of which have been machined, over the endurance limit of unmachined specimens.

Influence of Annealing and Stress Relieving and Residual Stress

Annealing.—Annealing at from 880 to 920°C. (1616 to 1688°F.) lowers the endurance limit of welds having a medium or high nitrogen content (above about 0.04% N) but raises the endurance limit if the nitrogen content is below 0.04%. The difference in endurance limit between the as-welded and the annealed specimens is never more than 3000 psi.

Stress Relieving Heat Treatment.—Reports on the effect of stress relieving (by heating to about 600°C. (1112°F) on the endurance limit of welds are somewhat conflicting. It seems quite possible that stress relieving increases the notched impact values more than it does the fatigue strength values.

Shrinkage Stresses.—Internal stresses in ductile welds are diminished by the minute plastic yielding which occurs under repeated loads even though the computed stresses are below the static yield strength of the metal. For brittle welds internal stresses are effective in lowering the endurance limit.

Influence of Alloying Elements, Including Copper

Carbon Content.—A carbon content of the base metal between 0.25 and 0.60% has only a slight effect on the reverse bend endurance limit of butt welds.

Low Alloy Steels.—Welds in low alloy steel have satisfactory values of endurance limit but low-alloy steels have only slight advantage over mild steel, except at high values of superimposed tension, under which condition the high elastic strength of the low alloy becomes important.

Alloy Steels.—V-butt welds made by the atomic hydrogen process on plate with the following chemical composition: 0.28-0.35% C; 0.5% Mn; 1.1% Cr; 2.0% Ni; 0.25–0.40% Mo, have been studied by using a rotating-beam fatigue machine of the cantilever type. The endurance limit depends greatly on the filler metal used. Welds made with chromium-molybdenum gave higher values of endurance limit than welds made with chromium-nickel or 3.5% nickel electrodes. These last-named tests were made with base metal containing 0.32% C and 3.4% Ni on an Upton-Lewis reversed-bend fatigue machine. Welds in plate containing 3.5% Ni withstood 20 times as many cycles of stress at 30,000 psi. as did welds in plain medium-carbon plate. For tests of both plates a low-carbon electrode (0.13–0.18% C) gave better results than a chromium-vanadium electrode (0.89% Cr, 0.15% V) or a nickel-chromium electrode (1.0% Ni, 0.5% Cr).

Cast Steel and Cast Iron.—The rotating-beam endurance limit of cast steel welds made with bare electrodes is 15,800 psi., for specimens with the cast skin removed. The decrease in endurance limit due to welding is proportionately less than the decrease in tensile strength. Annealing does not increase the endurance limit. The rotating-beam (cantilever) endurance limit of gas-welded gray cast iron, one inch thick and welded with cast iron welding rod, is 12,000 psi., the endurance limit of the unwelded cast iron is 13,500 psi. The welds were 45° V-welds, and the chemical composition of the cast iron was 3.46% total C; 0.74% combined C; 0.106% S; 0.66% Mn; 1.33% Si; 0.282% P.

Fatigue Test Results for Welds in Non-Ferrous Metals

Only one investigator, Bartels, has made an extensive study of the fatigue properties of welds in non-ferrous metals and alloys.

Table 2 summarizes his results.

Table 2—Rotating-Beam Fatigue Strengths of Acetylene Welds in Non-Ferrous Metals. (Bartels)

Metal	Tensile Strength, Psi.		Endurance Limit for 10,000,000 Cycles of Stress, Psi.		
	Unwelded	Welded	Unwelded	Welded	Welded and Annealed
Copper	39,000	17,700	12,100	5,700	6400
Aluminum	17,400	13,400	8,500	8,500	..
Silumin*	19,500	6,250	7,800	10,700	5000
Copper silumin†	16,600	10,100	9,300	11,400	..

* Chemical composition of silumin: Si 10.14%; Cu 0.46%; Fe 0.70%; Al remainder.
† Chemical composition of copper silumin: Si 9.8%; Cu 1.03%; Fe 0.77%; Al remainder.

Fatigue Strength of Welded Pressure Vessels

Tests of steel shells 42-in. inside diameter under repeated cycles of intermittent hydraulic pressure were carried out in the early days of advancement in the art of fusion welding in the laboratories of the Babcock & Wilcox Co. at Barberton, Ohio. The result of these tests and the developments made in connection therewith had much to do with the acceptance of fusion-welded drums for boilers by the U. S. Navy and the inclusion of rules for the welding of drums for power boilers in the A.S.M.E. Boiler Code. The steel in the shells was a plain carbon steel with a required minimum tensile strength of 55,000 psi. A summary of typical test results is given in Table 3.*

In making fatigue tests of small specimens of steel six or more specimens are tested under various stresses, and one or more tests run to 10,000,000 cycles. Then a *S-N* diagram is plotted as shown in Fig. 4 (*a*) and the endurance limit determined. This procedure is not feasible for testing full-size test shells. It is necessary to cut down the number of specimens, and it is rarely feasible to carry tests to a large enough number of cycles to determine the endurance limit for an indefinitely large number of cycles. However, in the ordinary term of service of a pressure vessel the cycle of stress caused by internal pressure is repeated but a few thousand times, and it is found feasible to obtain some idea of a cycle of stress which can be repeated without causing fracture for many times the number of cycles in the normal "lifetime" of the pressure vessel. The commonest cycle of stress to which pressure vessels are subjected is pulsating stress varying from zero to a maximum (range ratio equals zero). The cycle of pressure used in the Barberton tests ranged from zero to 1570 psi. This was well above the working pressure allowed by the A.S.M.E. code as may be seen from Table 3.

* For a more detailed account of these tests see *Transactions*, Am. Soc. of Mechanical Engineers, Fuels and Steam Power, *53* (1), 55-64 (January–April 1931).

Table 3—Fatigue Test Results on Welded Test Shells Under Repeated Internal Hydraulic Pressure

Each shell 42 in. inside diameter; welded plates 2 in. thick; forged shell without seam 1 7/8 in. thick; welded shells one longitudinal seam

Test Shell No.	Type of Weld	Maximum* Allowable Working, Psi.	Range of Test Pressure, Psi.	Range of Circumferential Tensile Stress, Psi.	Number of Cycles Pressure	Fracture
..	Forged shell, no weld	1047	0–1570	0–18,000	446,950	At 1/2-in. tapped hole for gage
12	Forge-and-hammer weld	665	0–1570	0–16,500	890,500	Did not fracture
13	Forge-and-hammer weld	665	0–1570	0–16,500 0–14,650†	611,164	In plate away from weld at a long. defect in inside surface
1	Arc-welded, bare wire	838	0–1570	0–16,500	5,530	In long. seam near middle of length at junction of base metal and weld metal
2	Arc-welded, coated wire	838	0–1570	0–16,500	267,603	Through slag inclusion in weld
3	Arc-welded, coated wire	838	0–1570	0–16,500	417,381	At 1/2-in. tapped hole for gage
4	Arc-welded, coated wire	838	0–1570	0–16,500	561,984	At 1/2-in. tapped hole for gage
5	Arc-welded, coated wire	838	0–1570	0–16,500	435,883	At 1/2-in. tapped hole for gage
6	Arc-welded, coated wire	838	0–1570	0–16,500	58,842	At tapped hole located in weld. Hole very irregular at inner surface
7	Arc-welded, coated wire	838	0–1570	0–16,500	1,035,037	Did not fracture
8	Arc-welded, coated wire	838	0–1570	0–16,500	1,995,450	Did not fracture

* By A.S.M.E. Power Code.
† Stress in plate 16,500 psi.; stress in weld (2 1/4 in. thick) 14,650 psi.

Table 4—Fatigue Strength of Butt Welds in 7/8-In. Carbon-Steel Plates

Description of Specimen	Fatigue Strength in Thousands of Psi.					
	Tension to an Equal Compression		Zero to Max. Tension		Tension to Tension 1/2 as Great	
	N = 100,000	N = 2,000,000	N = 100,000	N = 2,000,000	N = 100,000	N = 2,000,000
As welded	22.3	14.4	33.1	22.5	53.3	36.9
Reinforcement on stress relieved	21.3	15.1	31.9	23.7	..	37.6
Reinforcement machined off, not stress relieved	28.9	..	48.8	28.4	..	43.7
Reinforcement machined off, stress relieved	24.5	16.6	49.4	27.8	..	42.6
Reinforcement ground off, not stress relieved	26.8	..	44.5	26.3	..	..
Plain plate, mill scale on	27.7	17.1	49.8	31.7	..	50.0
Plain plate, mill scale machined off, surface polished	..	..	59.6	..	..	..
Butt weld, reinforcement and mill scale machined off, surface polished	..	..	53.9	..	..	..

The tests offer evidence that properly made arc-welded joints in boiler shells and other cylindrical pressure vessels offer greater resistance to repeated stress than the plates themselves, if the plates are weakened by rather small surface defects or by tapped holes, which are very effective "stress raisers." The failure at a tapped hole of the forged test shell, which was without any welded seam, is of interest in this connection. The short "life" of the test shell welded with bare welding wire is of interest, as is the failure of one test shell by a crack starting from a slag inclusion in the weld. Test shells 7 and 8 withstood nearly double the allowed working pressure for a number of cycles of pressure far greater than would probably occur in the service of most, if not all, pressure vessels.

Data on fatigue tests of full-size shells at elevated temperatures are not available, but, judging from fatigue test results on small specimens, their strength would not seem likely to be much reduced unless subjected to temperatures as high as 500° or 600°F.

Fatigue Strength of Structural Parts

A comprehensive series of fatigue tests of double-V butt welds in $^{7}/_{8}$-in. carbon steel plates has been made as a part of the work of Committee F, Fatigue Committee (Structural) of the Industrial Research Division of the Welding Research Committee of the Engineering Foundation. The details of the specimens are shown in Fig. 6. The plates had a carbon content of 0.25% and a manganese content of 0.48%. All welds were laid in the flat position by a qualified welding operator using an all-position shielded arc electrode. Radiographs were taken of all specimens and the welds were found to be free of all but minor defects and were probably a little more uniformly good than most commercial welds. The fatigue strength was determined for failure at both 100,000 and 2,000,000 cycles. The stress ranges used included tension to an equal compression, 0 to a maximum tension, and a maximum tension to a tension one-half as great. Some specimens were tested in the "as-welded" condition, some were stress-relieved by heat treatment and some had the reinforcement planed off flush with the base plate. Similar tests were also made of specimens similar to the one shown in Fig. 6, except that each consisted of a plate without a weld, the specimens being cut from the same parent plate as the plates of the welded joints. A summary of the results of the tests is given in Table 4. The same data are presented graphically by the diagrams of Fig. 12. The small circles connected with broken lines represent the results of the tests and the full lines represent the empirical equation $(FL)' = 3(FL)/(2 - r)$, in which (FL) is the fatigue strength under complete reversal, r is the ratio of the minimum to the maximum stress (negative for a reversal of stress) and $(FL)'$ is the fatigue strength for a given r. The numeral adjacent to a small circle indicates the number of tests averaged.

The following conclusions, based upon the values given in Table 1 and Fig. 12, are quoted from the report of the tests:*

"For specimens in the as-welded condition, the values of the fatigue strength for a cycle in which the stress varied from tension to an equal compression were 22,300 psi. for failure at 100,000 cycles and 14,400 psi. for failure at 2,000,000 cycles; and for a cycle

* See University of Illinois Engineering Experiment Station, *Bulletin No. 327*.

in which the stress varied from 0 to tension the values of the fatigue strength were 33,100 psi. for failure at 100,000 cycles and 22,500 psi. for failure at 2,000,000 cycles.

"For specimens in the as-welded condition except that the reinforcement had been machined flush with the base plate on both sides, the values of the fatigue strength for a cycle in which the stress varied from tension to an equal compression were 28,900 psi. for failure at 100,000 cycles and 16,850 psi. for failure at 2,000,000 cycles. These values are considerably higher than corresponding values reported in the preceding paragraph for similar specimens with the reinforcement on.

"A comparison of the fatigue strength of butt welds that have been stress-relieved by heat treatment with the fatigue strength of those that have not been stress-relieved indicates that stress-relieving did not affect the fatigue strength. This was true for the specimens with the reinforcement off as well as for those with reinforcement on.

"Specimens from which the reinforcement had been machined flush with the base plate on both sides had approximately the same fatigue strength as plates without welds but with the mill scale on.

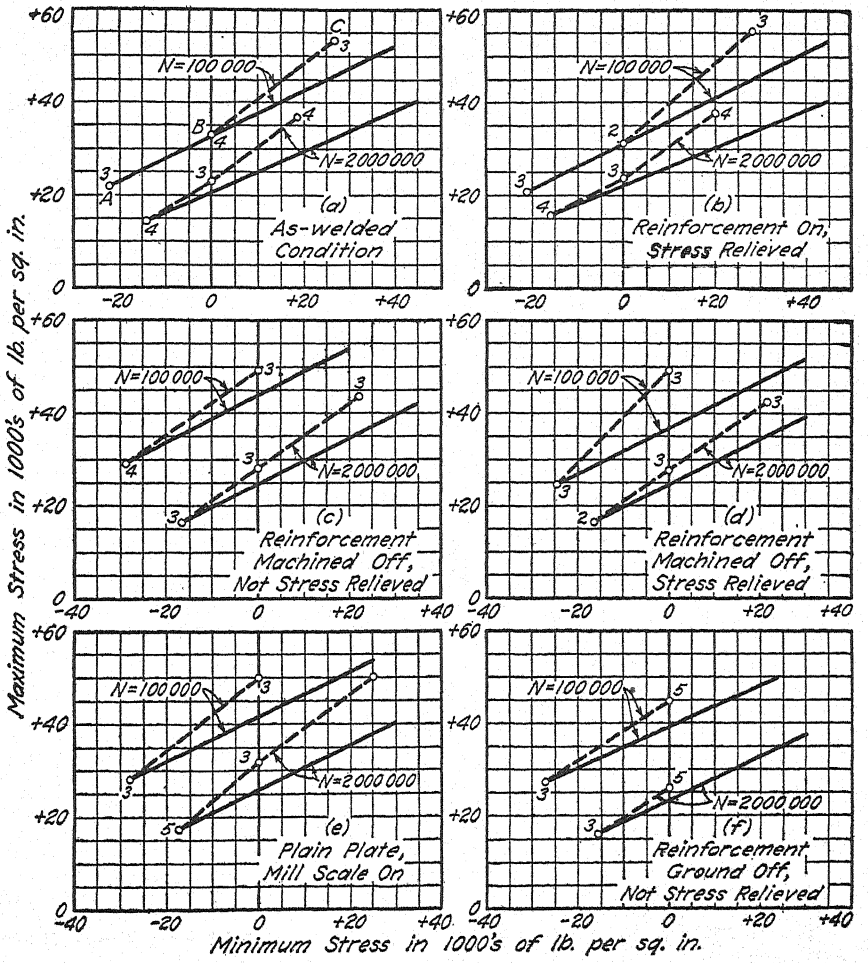


Fig. 12—Fatigue Strength of Butt Welds in 7/8-In. Carbon-Steel Plates for Various Types of Specimens and Various Ranges of Stress

"Specimens from which the reinforcement had been ground flush with the base plate on both sides with a portable grinder had a fatigue strength only slightly lower than that of similar specimens with the reinforcement machined off.

"Specimens with the reinforcement and mill scale machined off and the surfaces polished had a fatigue strength somewhat greater than that of specimens with the mill scale on but considerably lower than that of small round machined and polished specimens. This latter may be due to the 'size' effect.

"For all kinds of specimens, stress-relieved or not stress-relieved, reinforcement off or reinforcement on, the fatigue strength corresponding to failure at 2,000,000 repetitions of a cycle in which the stress varied from tension to tension one-half as great, exceeded the yield point of the material and is therefore not important to the structural designer."

Effect of Periods of Rest Upon the Fatigue Strength of Butt Welds in Carbon Steel Plates

The question has been raised as to whether or not the results of fatigue tests run continuously in a laboratory are applicable to field structures which are subjected to intermittent service. Committee F planned a series of tests to answer this question. The specimens consisted of single-V butt welds in $^1/_2$-in. steel plates for which the carbon, manganese and silicon contents (per cent) were 0.27, 0.45 and 0.01, respectively. The specimens were 3 in. wide at the weld. The following paragraphs are quoted from the report.*

"The method of making the tests was as follows:

"Nine specimens, as nearly as possible identical, were selected for a series to be tested at a given cycle, the maximum stress in the cycle and the ratio of the minimum to the maximum stress being the same for all specimens. Three were tested continuously, three were tested with 5-min. rest periods following each 100 cycles and three were tested with 30-min. rest periods following each 100 cycles. Some series were planned for failure at 100,000 cycles, others for failure at 2,000,000 cycles. The latter, however, did not include the tests with 30-min. rest periods because of the great length of time that would be necessary for such a test.

"A summary of the results is given in Table 5, each value representing the average of three tests.

"The data contained in the table indicate that rest periods decrease the fatigue strength, and that the longer the rest period the less is the indicated fatigue strength.

Table 5—Effect of Rest Upon Fatigue Strength of Butt Welds in ½-In. Carbon-Steel Plates

		Fatigue Strength*				
	Stress in Thousands of Psi.	N = 100,000† No Rest	5 Min. Rest	30 Min. Rest	N = 2,000,000† No Rest	5 Min. Rest
Complete reversal	+20.0 to −20.0	20.1	20.5	19.8* 20.2	..	..
	+16.0 to −16.0	..	..	..	15.4	14.2‡ 13.8
Zero to max. tension	0 to +27.0	..	..	..	25.6	23.8
	0 to +30.0	..	34.3	..	27.2	..
	0 to +35.0	37.6	..	34.9	..	..

* Each value represents the average of three tests.

† N represents the number of cycles for fracture.

‡ Two groups of three tests each at this rest period with average fatigue strengths as shown.

* Report No. 1, Committee F. A detailed report of the tests is contained in University of Illinois Engineering Experiment Station. *Bulletin 327.*

The average difference between the rest and no-rest strengths was 5%; and the maximum difference was 10%.

"The Committee interprets the results of these tests to indicate that rest periods have no significant effect upon the fatigue strength of welded joints in such a steel, when these joints are made and tested under conditions approximately those met in general structural work; and that this conclusion may be extended to welded joints in steel of the standard grade for bridges and buildings."

The Effect of Transverse Fillet Welds Upon the Fatigue Strength of Steel Plates

Tests were planned by Committee F to determine the effect of transverse fillet welds upon the fatigue strength of steel plates. Three types of

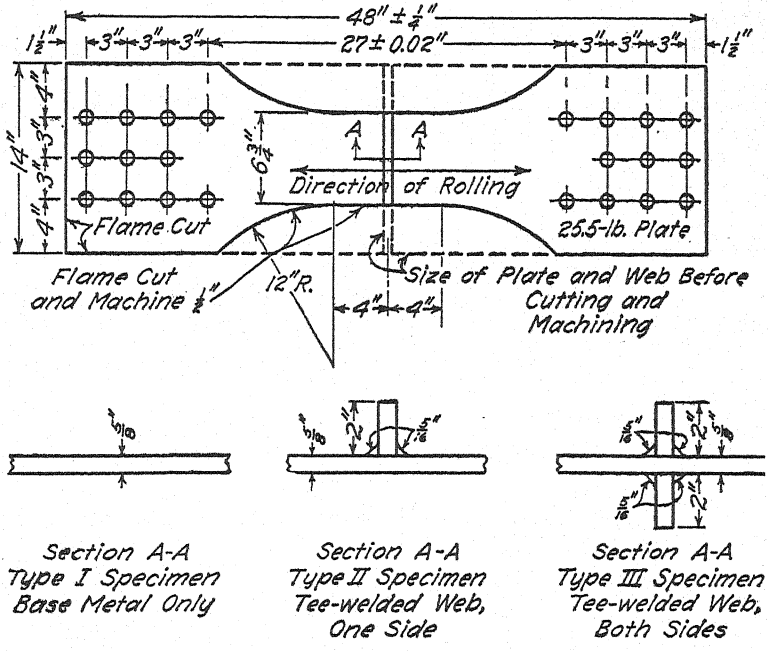


Fig. 13—Specimens for Determining the Effect of Transverse Fillet Welds Upon the Fatigue Strength of Steel Plates

specimens were used, the details of which are shown in Fig. 13. Type I was a continuous plate without welds or joints and with mill scale on both sides; Type II had a narrow transverse plate attached to one side of the main plate with two transverse fillet welds; Type III had transverse plates attached to both sides of the main plate. The main plate was continuous for all three types of specimens.

Specimens of each of the three types were made of two grades of steel, a medium-grade carbon steel and a low-alloy steel. Each of the six groups contained six identical specimens that were tested in fatigue on a cycle in which the stress varied from tension to an equal compression.

The carbon-steel plates had a yield point of 34,500 psi., an ultimate strength of 58,700 psi., an elongation in 8 in. of 30.7% and a reduction of area of 55.1%.

The alloy had a yield point of 59,100 psi., an ultimate strength of 78,900 psi., an elongation in 8 in. of 20.5% and a reduction of area of 61.5%.

Table 6—Fatigue Strength of Plates with Transverse Fillet Welds

During a cycle the stress varied from tension to an equal compression

Steel	Type of Specimen	Average Fatigue Strength, Thousand Psi. N = 100,000*	N = 2,000,000*
Plain carbon	I	25.8†	22.8
	II	25.4	18.9
	III	22.9	13.1
Low alloy	I	35.3	26.4
	II	31.7	23.9
	III	22.2	10.1

* N denotes the number of cycles of stress for failure.
† Each value is the average of three tests.

A summary of the results of the tests is given in Table 6, each value being the average of three tests.

The following paragraphs are quoted from the full report of the tests.*

"The fatigue strength of the Type I and Type II specimens was significantly greater for the alloy steel than it was for the carbon steel. For the Type III specimens the fatigue strength for failure at 100,000 cycles was approximately the same for both kinds but, for failure at a larger number of cycles, the fatigue strength was somewhat less for the alloy than it was for the carbon steel.

"The fatigue strength of specimens made of the alloy steel was considerably greater for the Type II specimens and somewhat less for the Type III specimens than the fatigue strength of single-V butt welds connecting plates of the same alloy steel."

Relative Fatigue Strength of Welded and Riveted Joints in Low-Alloy Steel Plates

Tests were planned by Committee F to determine the relative strength of welded and riveted joints connecting plates of a low-alloy steel of structural grade. There were nine each of riveted and welded specimens, six of the riveted specimens were subjected to fatigue tests and three to static tests. Of the welded specimens, seven were subjected to fatigue tests and two to static tests. The object of the static tests was to determine the strength of the joint and, for the riveted joints, to determine the load-slip relation.

All specimens were made of low-alloy structural steel plates approximately $^1/_2$ in. thick and weighing 21 lb. per sq. ft. and having C, Mn and Si contents (per cent) of 0.16, 1.27 and 0.20, respectively.

The riveted joints were of the double-strap butt type with $^3/_4$-in. manganese-steel rivets. The driven heads of the rivets were countersunk and chipped; the manufactured heads were of the button type.

The welded joints were of the single-V butt-weld type welded in a flat

* University of Illinois Engineering Experiment Station, *Bulletin No. 327*.

position using a shielded arc electrode such as is usually used for welding carbon steel plates.

The following conclusions are quoted from the full report of the tests.*

"The low-alloy structural steel plates had a static strength based on the gross area of 83,000 psi. when fabricated by welding and of 64,800 psi. when fabricated by riveting. The strength of the latter based on the net section was 85,000 psi.

"The low-alloy structural steel plates had a fatigue strength based on the gross area and corresponding to failure at 100,000 cycles of 25,000 psi. when fabricated by welding and of 19,800 psi. when fabricated by riveting. For failure at 2,000,000 cycles, the corresponding values were 15,000 psi. and 13,800 psi. for welded and riveted joints, respectively. These values of the fatigue strength are for a cycle in which the stress varied from tension to an equal compression.

"The fatigue cracks in the riveted specimens passed through the holes in the outer row. Those in the welded specimen began at the edge of the deposited metal where the abrupt change in section acted as a stress raiser that extended the full width of the specimen.'

Fatigue Strength of Machine Parts

The importance of fatigue strength of welded joints is recognized by the designer of welded machinery and in some codes maximum working stresses in fatigue have been established. Very few fatigue tests have been made on machines and in most cases endurance values obtained from simple joint tests are used.

When designing a welded structure subjected to fatigue it is important to keep in mind the harmful effect of stress raisers. Reinforcements, undercut, poor fusion, incomplete penetration and porosity are all stress raisers. Double welded joints are the best insurance against incomplete fusion at the root of a weld.

Fillet welds, because of their inherent shape, are a prime offender from the standpoint of stress raisers. The stress concentration at the toe of a fillet weld may lower the endurance limit of the base metal at that point to 10,000 psi. After a certain size weld is reached, the parent metal becomes the critical section and increasing the weld size will not increase the strength of the joint.

Special shaped butt straps with rounded or beveled ends are often used to reduce the stress raisers obtained by plain parallel and transverse fillet welds. Intermediate stress plates have been used between members, but they have been found to have no effect on increasing the endurance limit of the joint.

Reinforcing a butt joint with fillet welded butt straps has little or no effect in increasing the fatigue strength of the joint. In many cases the strength may actually be reduced.

The endurance limit of intermittent fillet welded joints subjected to tension-compression loading is lower than that of a continuously welded joint. One investigator recommends, for intermittent welds, and continuous fillet welds, allowable stresses 60% and 85%, respectively, of the allowable stress in the base metal.

Investigations to determine the feasibility of welding wheel spokes directly to a 0.45 C shaft rather than to an intermediate hub indicate that the endurance limit of the shaft is lowered to 7200 psi. because of the stress raisers. Changing the number of spokes from 4 to 6 had no effect.

* University of Illinois Engineering Experiment Station, *Bulletin No. 327.*

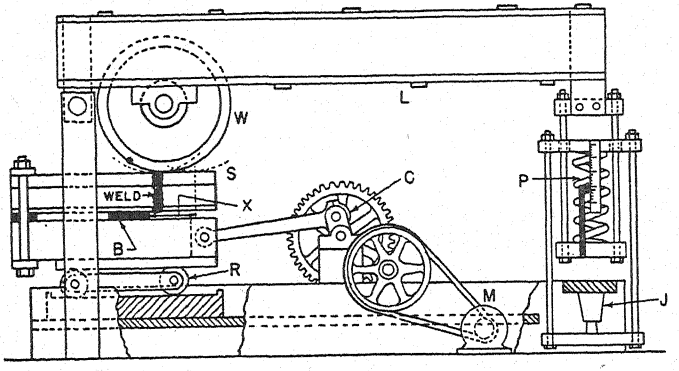


Fig. 14—Rolling-Load Testing Machine for Fatigue Tests on Welded Rails

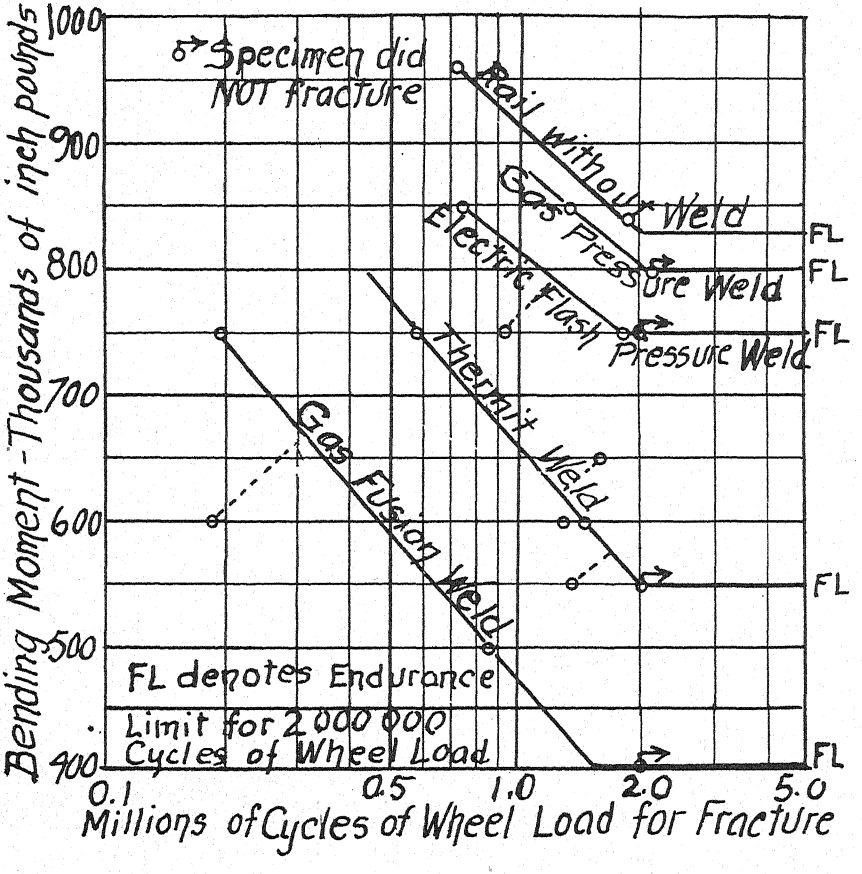


Fig. 15—S-N Diagrams for Fatigue Tests of Welded Rail

Fatigue Strength of Welded Railroad Rails

Tests of full-section specimens of welded railroad rails, sponsored by the Association of American Railroads, have been carried on in the Talbot Laboratory at the University of Illinois.* The testing machine used for these tests is shown in Fig. 14. The welded joint specimen S is pulled backward and forward under the wheel W, the load on which can be varied from zero to 75,000 lb. by means of the screw jack J and the lever L. The load is measured by the compression of the spring P. The stroke of the machine is 12 in., and the speed 60 rpm.

Three or more specimens of each type of welded joint were tested for each of two weights of rail, 112 and 131 lb. per yard (except for the resistance flash pressure welded specimens which were furnished for 131-lb. rails only). The specimens of each group were tested under a series of loads, 75,000 lb. for the first specimen, and successively lower loads for the other specimens. Then S-N diagrams were drawn. Figure 15 shows S-N diagrams for the 112-lb. specimens. The endurance limit was determined for 2,000,000 cycles of stress, and the cycle of stress was a cycle of wheel

* Proceedings, Am. Ry. Eng. Assn., **40**, 687–713 (1939) and **41**, 737–765 (1940).

Table 7—Endurance Limits for 2,000,000 Cycles of Rolling Wheel Load on Welded Rail Specimens and Rail Specimens Without Welds

In the rolling-load test the head of the rail specimen is subjected to cycles of tensile stress (flexural) varying from zero to a maximum

	At Endurance Limit				
Type of Joint	Wheel Load, Lb.	Maximum Bending Moment, In.-Lb.	Maximum Tensile Stress (Flexural), Psi.	Maximum Shearing Stress, Psi.	Ratio of Strength to That of Rail without Weld, %
		Rail 112 lb. per yard			
Rail without weld	62,500	750,000	41,600	25,400	100
Gas fusion weld (Process A)	39,000	390,000	21,600	15,800	62*
Gas fusion weld (Process B)	28,000	280,000	15,600	11,400	45*
Thermit weld	49,000	490,000	27,200	20,000	78*
Electric pressure butt weld			No specimens of welded 112-lb. rails		
Gas pressure butt weld	58,000	580,000	32,200	23,600	78†
		Rail 131 lb. per yard			
Rail without weld	69,200	830,000	36,600	21,300	100
Gas fusion weld (Process A)	40,000	400,000	17,600	12,300	58*
Gas fusion weld (Process B)	19,000	190,000	8,400	5,900	27*
Thermit weld	55,000	550,000	24,200	17,000	79‡
Electric pressure butt weld	75,000	750,000	33,000	23,100	90†
Gas pressure butt weld	80,000	800,000	35,200	24,700	96†

* Failure by internal fissure; strength ratio based on wheel load.
† Failure by flexural stress; strength ratio based on bending moment.
‡ Failure in web (shearing stress); strength ratio based on wheel load.

load, bending moment and shearing stress ranging from zero to a maximum with the rail head in tension.

Extensive field tests of stresses set up in rail under traffic indicate that in the normal "life" of a rail on straight track about 100,000 cycles of heavy wheel load (40,000 lb. or higher) might be expected. The selection of 2,000,000 cycles for determining the endurance limit is somewhat arbitrary, and the determination of endurance limit less definite than is the case for small specimens, but the results are believed to have a comparative value for the different types of weld.

Three types of fractures were found in the specimens tested; (1) failure by flexural stress starting from a point on the tread of the rail, (2) failure by shearing stress in the web and (3) failure by a transverse fissure starting from some imperfection in the interior of the head of the rail. Rolling-load tests of short lengths of rail without any welded joint were also made. The chemical composition of the steel in the rails ranged between the following values: C, 0.70–0.73%; Mn, 0.76–0.80%; Si, 0.15–0.20%; P, 0.020–0.023%; S, 0.022–0.037%.

Table 7 shows the ratio of fracture strength under the rolling-load test of rails with welded joints and rails without welded joint. The values of strength are based on a "life" of 2,000,000 cycles of rolling load.

While these rolling-load tests of welded rails are too few to serve as a basis of any precise evaluation of the strength of welded rail, yet they offer some evidence that under the repeated loading to which railroad rail is subjected the electric flash butt-welded rails and the pressure-welded rails using gas (acetylene) for heating developed a minimum of 78% and an average of 88% of the strength of a rail without weld. The thermit welds developed about 78% of the strength of the rail without weld. The fusion welds (oxyacetylene) without pressure were weaker than the other types of welded rail.

CHAPTER 34C

CORROSION RESISTANCE OF WELDED JOINTS*

Design of Joints, Flux Removal, Stress Corrosion, Steel, Mild Steel, Low Alloy Steel, Galvanized Steel, Bronze-Welded Joints, Flame-Cut Surfaces, Stainless Steels, Welds at Elevated Temperatures, Nickel and Alloys, Aluminum and Its Alloys, Magnesium and Its Alloys, Copper and Its Alloys, Lead and Its Alloys, Soft Soldered Joints

IN the case of many metals and alloys under many of the common conditions of exposure, no special attack at or adjacent to the welds ordinarily occurs. However, since the weld metal often differs chemically or metallurgically from the parent metal, in specific solutions or under certain conditions of exposure special attack at or adjacent to the welds may occur. As a rule there is less likelihood of such special attack if the weld metal is of the same composition as the metal being welded, particularly if the welded parts are annealed or given a solid solution heat treatment after welding. It is important to secure welds that are free from pinholes, cold shuts, trapped slag or other mechanical defects. Such imperfections may well provide a starting point for attack by corrosion.

There are no text or reference books devoted entirely to corrosion properties of welds but some articles on this subject have been published in technical periodicals. Also, especially in the case of the stainless steels and nonferrous metals, manufacturers have accumulated a store of specific data on corrosion under various conditions.

Design of Joints

The design of welded joints is sometimes of importance in determining how well a given joint will resist a specific exposure. In general, lap joints designed so that moisture can penetrate and be trapped between the faying surfaces are more subject to selective attack than are other types of joints that do not permit the access of liquid between the faying surfaces. The special attack occurring at such lap joints is probably the result of concentration cells set up between the liquid at faying surfaces and the liquid in contact with the exposed surfaces of the weld metal. As is mentioned subsequently, the presence of residual flux sometimes causes special

* Prepared by a committee consisting of J. R. Dawson, Union Carbide and Carbon Research Labs. *Chairman;* F. L. La Que, International Nickel Co.; R. B. Mears, Aluminum Company of America.

corrosion. Joints designed so that flux can be easily removed are, therefore, less likely to exhibit attack from this cause than are joints from which it is impossible completely to remove residual flux.

Flux Removal

Many types of fluxes are corrosive to the metals or alloys with which they are used. Therefore, it is important that in most cases residual flux be removed from the metal surface immediately after the welding operation. Methods of removal generally employed include mechanical methods such as scratch brushing, rinsing or scrubbing with water, and exposure to acid or other chemical dips. The best method to use in any given case depends on the metal or alloy that has been welded and the type of joint made.

If the welded article is subsequently to be painted or given chemical or anodic treatments, flux removal usually is especially desirable, since residual flux can cause blistering of the paint and severe local attack on the welded article during the chemical or anodic treatments.

Stress Corrosion

It is well known that stress may influence corrosion of the material to which it is applied and, since local stresses, such as may be developed in welding operations, are likely to have more adverse effect than uniformly distributed stresses, it is frequently desirable to give welded structures a stress-relieving or stress-equalizing anneal after welding.

Metals and alloys vary considerably with respect to their susceptibility to stress corrosion, and with each material there is a limited number of specific corrosive media in which stress corrosion is most likely to occur. Consequently, it is necessary to be guided by past experience and manufacturers' recommendations in determining whether stress-relief annealing after welding *must* be applied in any given case.

The substitution of welded for riveted joints has been found to be useful in removing opportunities for concentration of salts in crevices, a contributing cause of caustic embrittlement, which is a particular form of stress corrosion often encountered in steel boilers.

The possibility of stress corrosion of welded structures should be considered in planning and carrying out corrosion tests leading to the choice of material for a service in which there has been no past experience.

Steel, Cast Iron and Wrought Iron

Welds in 6-in. diameter pipes made of seamless steel, cast iron and wrought iron, were exposed to atmosphere, soil immersion, alternating tap water and atmosphere, salt spray, electrolysis in salt water and 15% HCl. Arc welds with coated electrodes and gas welds in steel both resisted corrosion under these exposures equally as well as the base metals. Arc welds with bare electrodes were attacked much more severely than the base metal. With the coated electrodes there was no difference in the corrosion resistance of arc welds made with direct and with alternating current. Bronze welds in steel and cast-iron pipes did not result in undue corrosion of these base metals.

Mild Steel

Good welds made in mild steel by the arc process with coated electrodes and by the gas process are not subject to excessive corrosion as compared with the base metal in tap water, boiler feed water, gasoline, sea water or salt water spray. Generally, arc welds with bare electrodes are attacked more severely than the base metal when exposed to these corroding media.

Carbon Arc Welds.—Carbon arc welds in mild steel made under a shielding gas have better general corrosion resistance than carbon arc welds not so shielded.

Forge Welds.—Tests of good forge welds have indicated that the welds are equal to the base metal in resistance to corrosion.

Submerged Melt Welds.—In general submerged melt welds in mild steel resist corrosion equally as well as the base metal.

Mild Steel Welds vs. Rivets.—Whatever difference there may be between the corrosion resistance of riveted and welded joints under corrosive conditions appears to be in favor of the welded joint. Caustic embrittlement is not ordinarily encountered in good quality butt welds.

Electrochemical Potential.—Differences are very small in the electrolytic potential between good quality steel weld metal and its adjoining mild steel base metal, and so electrolytic action between such welds and base metal is unlikely to result in serious attack by corrosion. So long as the weld metal is more noble than the base metal even large differences in composition between base metal and weld metal may not lead to local corrosive attack, as, for example, in the case of austenitic welds in mild steel, or bronze welds in mild steel or cast iron.

Low Alloy Steel

Low alloy steel base metal or weld metal containing chromium, copper or nickel, has somewhat greater resistance to corrosion than plain mild steels. In general, well-reinforced welds of good quality made by either the arc or gas process in low alloy steels will give the same length of service under corrosion as the base metal.

Galvanized Steel

Arc and gas welds made with steel rods in galvanized steel require some protective coating if they are to equal the galvanized steel in resistance to corrosion. The zinc coating on either side of the weld and on the underside of single-vee welds is damaged so that the corrosion resistance of the steel is low. Gas welds made with bronze rods are not attacked in the service for which galvanized steel is ordinarily used but the zinc coating adjoining the weld is damaged to some extent. The service in respect to corrosion of galvanized iron acetylene generators, with bronze-welded joints, has been satisfactory. Usually some inhibitor against rusting is added to the water in the generator.

Bronze-Welded Joints

Mild steel and cast iron are frequently gas welded with bronze rods, and electrolytic action or preferential corrosion of either the weld or base metal

by the media in which mild steel and cast iron are ordinarily used is not generally observed. Cast-iron bronze-welded specimens resist corrosion in sea water and in most corrosive soils.

Flame-Cut Surfaces

In most instances flame-cut surfaces in mild steel have better corrosion resistance than planed surfaces.

Welds at Elevated Temperatures

Welds in mild or low alloy steel when of approximately the same composition as the base metal, have been as satisfactory as the base metal in resistance to corrosion.

Stainless Steels

Stainless steels, designed primarily for corrosion resistance, may be grouped as follows:

Plain chromium steels containing from 12–25% chromium.

Austenitic steels containing approximately 17–25% chromium and 7–25% nickel. (In some austenitic steels various amounts of the nickel may be replaced by manganese.)

The corrosion resistance of these steels is attributed to the formation of a passive film or oxide on the surface. In general, the resistance to corrosion increases with the chromium content and the resistance to the non-oxidizing type of corrosion is markedly increased by the addition of nickel. The corrosion resistance of austenitic steels is further enhanced in a considerable number of media by the addition of molybdenum.

Satisfactory fusion welds with corrosion resistance approximating that of the parent metal are made in all of these steels. Also, in various instances stainless steels, generally of the austenitic type, are used successfully to resist corrosion when welded by electrical resistance methods such as flash, spot and seam welding. Stainless clad steel is welded by fusion methods, and vessels made of this material are used extensively in a variety of corrosive media. Steel equipment is often protected by liners consisting of thin sheets welded in place to provide a complete covering.

In most instances a given stainless steel is welded with rods that will give weld metal of approximately the same composition as the parent metal. If, however, for some reason a rod of a different composition is used, care must be exercised to insure that the weld metal is at least as corrosion resistant as the base metal. The welding of these steels presents some difficulties not ordinarily met with in working with mild steels. For example, the corrosion resistance is adversely affected by increase of carbon, so generally effort is made to maintain the carbon content under 0.1% in both the parent and base metals.

The straight chromium steels in the as-welded condition are subject to loss of ductility of the weld, and in some media the areas adjacent to the welds are less resistant to corrosion than the unaffected base metal. Heat treatment after welding, at 740° to 870°C. (1350° to 1600°F.) for a few hours restores the corrosion resistance and makes some improvement in the physical properties.

The plain austenitic type steels of the 18–8, 25–12, 25–20 chromium-nickel types in the as-welded condition are subject to intergranular corrosion or "weld decay" in the parent metal adjacent to the weld, and this condition is still more marked in the case of structures in which the welds intersect. This condition may be corrected by heat treatment at 1050°C. (1920°F.) or higher. It is prevented by the use of columbium or titanium in the parent metal and of columbium in the weld metal. In most instances the carbon content is maintained at 0.08% maximum with a titanium to carbon ratio of 4:1 to 5:1 or with a columbium to carbon ratio of from 6:1 to 10:1, depending upon the requirements of the service.

The addition of molybdenum for improvement in general corrosion resistance of the base metal does not eliminate "weld decay (intergranular corrosion)." This condition may be prevented by using materials that contain columbium, or by heat treatment after welding. The elements molybdenum and columbium are ferrite formers that tend to unbalance the austenitic structure of the 18–8 chromium-nickel steels with consequent lowering of corrosion resistance in some media, but the correct balance can be maintained by increase of nickel content in the steels containing molybdenum or columbium or both. Only as much molybdenum is used as is required by the service, and the nickel content in both base metal and weld metal is increased to 12–14%.

Somewhat higher chromium and nickel contents in welding rods than in the base metal are often employed to offset loss of chromium that occurs when the metal is melted, and to insure that enough nickel is present to give completely austenitic weld metal.

Corrosion (Oxidation and Scaling) of Welds at Elevated Temperatures

Heat-resisting alloys of the chromium-iron (Cr 5–30%), the chromium-nickel (Cr 20–30%, Ni 3–30%), and the nickel-chromium (Cr 8–20%, Ni 35–80%) types are being welded for high temperature service by the oxy-acetylene and arc methods.

When gas welding the straight chromium and the low nickel high chromium alloys, a neutral flame should be employed in order to preserve maximum corrosion resistance in the weld metal. The high nickel low chromium alloys require a neutral or slightly reducing atmosphere.

Welding rods for both gas and electric welding should be of the same composition as the material being welded, except that they should preferably have a little higher chromium content to allow for chromium depletion during welding.

Effects of the heating during the welding operation may impair oxidation resistance as well as liquid corrosion resistance. The inclusion of stabilizing elements will be effective in overcoming embrittlement of the weld and parent metal in structures required to operate in adverse temperature ranges.

It is imperative that all the flux be removed from all welded areas before the parts are placed in high-temperature service; otherwise a slagging action occurs that promotes rapid destruction of the alloy.

Nickel and Alloys

Monel, Nickel and Inconel.—Filler rods of substantially the same composition as the base metals are used so that welds have the same inherent corrosion-resisting properties as the parent metals. Best performance is assured by the selection of the proper welding rod and coating and the use of the proper technique for depositing weld metal so as to produce sound welds and avoid such defects as gas pockets, laps, undercutting and excessive slag inclusions. It is also desirable to remove residual flux.

Tests and experience have established that welds possessing satisfactory corrosion resistance can be made with Monel, nickel and Inconel by oxyacetylene, arc and resistance welding methods, the choice of method being determined generally by factors other than corrosion-resistance requirements.

Welds in Monel, nickel and Inconel clad steel are made preferably by the metallic arc method, using electrodes of appropriate composition. The recommended procedures minimize dilution of welds by iron from the base metal. Experience has shown that in the services for which these clad metals are used, such properly made welds demonstrate adequate corrosion resistance. In the case of Inconel clad steel, there has been some use of the more highly alloyed 80% nickel–20% chromium alloy rod in order to compensate for iron dilution of the welds.

The Hastelloys and Illium.—Procedures have been developed by which satisfactory corrosion resistant welds can be made with all the Hastelloy compositions.

Gas welding using filler rods of the same composition is preferred for Hastelloy A, B and C castings. It is desirable to use a special flux developed for the purpose and to keep the flame neutral in order to insure maximum corrosion resistance.

Wrought Hastelloys A and B are welded either with gas or by the metallic arc process, generally using filler metal of the same composition, though occasionally Hastelloy B rods are used for the welding of Hastelloy A. To insure maximum corrosion resistance, especially of gas-welded joints, these alloys should be heat-treated after welding by quenching the entire welded structure from 2100° to 2150°F.

Hastelloy D castings are preheated to a dull red heat and welded with gas, using rod of the same composition and a reducing flame. The welded castings should then be furnace-cooled.

Satisfactory corrosion-resisting welds may be made with either cast or wrought Illium, using rod of the same composition. Both metallic arc- and gas-welding methods are used. In gas welding, a reducing flame is preferred.

Aluminum and Its Alloys

General.—It is possible to weld all of the aluminum alloys. However, some alloys are better suited for welding than others. The tensile strength of all cold worked or heat-treated aluminum alloys is reduced by the heat of welding. Also, the resistance to corrosion of alloys 17S-T or 24S-T is appreciably reduced. These effects are usually less pronounced in the case of spot-welded joints than in joints produced by other methods of welding

Spot-Welded Joints.—The spots in spot-welded joints of aluminum alloys such as 2S, 3S, 52S, 53S and Alclad 3S are approximately as resistant to attack in most outdoor and "natural" environments as are the parent alloys themselves. There is no selective attack at spots in most environments unless some copper from the contact tips is deposited on the aluminum alloy surface. Areas with copper deposits are more readily attacked in certain environments, especially in seacoast or other saline exposures. The spots in spot-welded 17S-T and 24S-T are less resistant to attack than are the parent alloys, although they may be satisfactory for certain mild exposures. The spots in Alclad 17S-T and Alclad 24S-T, in many environments, have a very satisfactory resistance to attack, although they must be considered as possible points of weakness, especially if the sheet is melted through during the spot-welding operation.

Electric Arc-Welded Joints.—Carbon arc and atomic hydrogen welded joints are as resistant as the parent metal in most types of outdoor exposures. In certain chemical solutions, there is special attack at or adjacent to the welded zone, probably because of metallurgical transformations resulting from heating during the welding operation. These same comments apply to metallic arc welding, although in this case the nature of the welding electrode is another factor of importance. Filler rod of 43S alloy (5% silicon) is the standard coated electrode for metallic arc welding and has been found suitable for structural and architectural applications. However, when exposed to marine or saline environments, some selective attack at or adjacent to the weld may occur. In such applications, or those in which resistance to chemicals is desired, 2S filler rod or rods of alloys developed especially for the purpose usually form more resistant joints.

Gas-Welded Joints.—Gas-welded joints are made either with oxyhydrogen or oxyacetylene. Alloys such as 2S and 3S show no preferential attack at or adjacent to the welds upon atmospheric exposure, when welded with 2S filler rod. The same is true of alloys 52S, 53S and 61S, when welded with 43S filler rod. Upon exposure to specific chemicals, maximum resistance to corrosion is usually obtained when 2S filler rod is used for all of the alloys mentioned above. Also, in certain exposures involving chemicals, special attack at or adjacent to the welds may occur unless the welded articles are annealed or given a solution heat treatment after welding.

Brazed Joints.—There are three common types of brazing: gas, furnace and dip brazing. Gas-brazed joints are usually made with 43S or X716 alloy rod and a special low melting flux. The resistance to corrosion of brazed joints made with 43S is very similar to that of torch-welded joints made using this rod. Those made with X716 alloy have a somewhat lower resistance to corrosion in most environments, although they are adequately resistant for many purposes.

In making furnace-brazed joints either brazing sheet (which is a duplex product bearing a coating on one or both sides of a low melting aluminum alloy) or rods of 43S or X716 alloys are used. With brazing sheet or rods of 43S, the resistance of the joints to attack is very similar to that of gas-welded joints made of 43S alloy. When rods of X716 are used, the resistance of the joints to attack is somewhat lower than when 43S rods are employed. The brazing fluxes used with aluminum-base alloys are, in general, more corrosive than welding fluxes. Consequently flux residues must be

completely removed or failure from corrosion can be expected even in atmospheric exposure.

The same general remarks hold for flux-dip-brazed joints, except that removal of the flux subsequent to brazing becomes a more important problem in the case of such joints than in the other types of brazed joints. The presence of flux remaining on the surface of the specimen can cause severe attack in humid environments.

Magnesium and Its Alloys

Gas-Welded Joints.—Since the fluxes used in gas welding magnesium and its alloys are highly corrosive, simple butt joints from which the flux can be easily removed are recommended. Joints of this type made from rod having the same composition as the magnesium alloy being welded have as good resistance to corrosion in many environments as the parent sheet. In some cases, because of metallurgical transformations produced by heating, a band of selective attack will occur at or adjacent to the weld. Often such selective attack can be prevented by suitable heat treatments subsequent to welding. The occurrence of selective attack in any medium can usually be predicted by solution potential measurements of the various areas of the welded joint in that medium.

Resistance-Welded Joints.—Joints of these types in magnesium and its alloys often have as good resistance to corrosion as the parent sheet, provided the electrode tips are kept clean so that copper pickup is avoided. Generally it is also desirable to abrade the metal surface after welding, in order to remove copper particles. Chemical coating and painting of the entire surface are always required after a resistance welding operation (see Chapter 23).

Copper and Alloys

Copper.—Gas welding, preferably of deoxidized copper using rod of the same composition, or alloyed so as to lower the melting point slightly, is practiced most commonly, and produces welds that demonstrate satisfactory corrosion resistance. Similarly good results are obtained from carbon arc welds using silicon bronze or phosphor bronze rods which deposit weld metal that has adequate corrosion resistance without introducing complicating galvanic effects in the usual applications.

The use of high zinc (40%) brasses for brazing copper may lead occasionally to corrosion difficulties in environments in which the brass itself is vulnerable to attack which will be accelerated by the surrounding copper.

Brasses and Bronzes.—The most usual procedure with the common brasses and phosphor bronzes involves gas welding or brazing with a high zinc (40%) brass filler rod, which produces a joint having satisfactory corrosion resistance for most applications. For particularly severe corrosive conditions, phosphor bronze should be joined by silver soldering or carbon arc welding with phosphor bronze rod in preference to brazing with high zinc brass.

The silicon bronzes are particularly well adapted to welding by gas or arc-welding methods using rods of the same composition which yield deposits possessing corrosion resistance equal to that of the base metal.

The copper-nickel alloys that contain from 20 to 30% nickel can be welded readily by gas or arc-welding methods using filler rods of the same composition. Tests and experience with such welds, particularly in sea water, have shown them to possess excellent resistance to corrosion. Good results have been obtained also with metallic arc welds of the 30% nickel alloy using Monel filler rod. Gas welding is employed usually with the nickel silvers, particularly in architectural applications in which the corrosion resistance of the welds will match that of the base metal.

Lead and Its Alloys

Gas- or resistance-welded lead joints are generally equal to the parent sheet in resisting strong chemical solutions. Welded joints in lead-base alloys are also usually as resistant to attack as the parent alloy. Occasionally some selective attack at the weld occurs as a result of the inclusion of dross from the filler rod or of corrosion products from the sheets being welded.

Soft Soldered Joints

Soft soldered joints are usually not so resistant to corrosion as are brazed or welded joints. This is particularly true of soldered joints in metals such as aluminum or magnesium. For these alloys, soldered joints should not be used in wet or humid environments unless they are protected by suitable coatings. Soldered joints in iron-base, zinc-base or copper-base alloys are likely to be more resistant to attack. However, special corrosion of the solder or of the metal adjacent to it may occur in certain environments. Such selective attack can usually be predicted by suitable solution potential measurements. Zinc chloride fluxes, often used with iron, zinc or copper-base metals are corrosive. If such fluxes are employed, care should be taken to remove all flux residues after soldering.

CHAPTER 35

FACTORS AND DATA INVOLVED IN ESTIMATING COSTS

Manual Metal Arc-Welding Speeds, Electrode Requirements for Various Types of Groove Welds, Manual Oxyacetylene Welding Cost Data.

THE choice of a welding process for fabricating a given product is influenced by several factors, all of which should be thoroughly considered before a final selection is made.

Regardless of the type of welding to be used, the most important consideration affecting the over-all cost of the product is that of the design of the product. It has frequently been demonstrated that greater potential savings can be accomplished by changes of design than by any change of welding process or technique. In all cases it is extremely important for both economy and quality that the design is suitable for the particular welding process.

The following outline lists the most important factors which should be considered in arriving at a satisfactory and economical product:

1. Design of Product
   - *A.* Materials of Which Product Is Made
   - *B.* Physical Size and Shape
   - *C.* Thickness of Material
   - *D.* Types of Joint Required
2. Anticipated Production
3. Cost of Initial Installation
4. Fabricating Costs
   - *A.* Material Costs
     1. Plate Preparation
        - (*a*) Forming
        - (*b*) Joint Preparation
        - (*c*) Cleaning, if Necessary
     2. Filler Metal Costs
     3. Power or Gas Costs
   - *B.* Labor Costs
     1. Assembly and Tacking
     2. Welding
        - (*a*) Arc or Torch Time

* Prepared by a committee consisting of J. E. Waugh, General Electric Co., *Chairman;* L. C. Bibber, Carnegie Illinois Steel Corp.; G. C. Hill, Carnegie Illinois Steel Corp.; A. N. Kugler, Air Reduction Sales Co.; M. L. Smith, Metal & Thermit Corp.

(*b*) Changing Electrodes or Rods
(*c*) Cleaning Weld
(*d*) Handling or Positioning Work
(*e*) Moving About Work
(*f*) Personal Allowances

3. Chipping of Root

C. Maintenance of Equipment

D. Supervision Costs

1. Foremen
2. Inspection

This chapter is concerned primarily with the actual welding costs and confined to manual metal arc and gas welding of mild steel. These two processes are by far the most commonly used in industry at the present time. Data covering other welding processes such as machine welding with metal arc, gas and carbon arc processes, resistance welding, thermit and atomic hydrogen arc welding are included in other chapters of the HANDBOOK.

Welding labor costs are usually referred to as including assembly and tack welding of the component parts and the actual welding of the product, including incidental operations such as cleaning slag from the weld and chipping the root or defects as required.

Whenever practicable, in order to arrive at accurate costs, the assembly and tacking and any chipping should be segregated as individual items. They should in any event be considered as definite percentages of the total over-all labor.

The actual welding time consists of arc or torch time, changing electrodes, cleaning the weld, handling or positioning the work, moving about the work to be in the correct position to weld and personal allowances. The largest single factor of these is the arc or torch time, which for a given condition of weld size with a given electrode type and size, current and voltage or tip size and gas consumption can be very definitely controlled. All of the other factors will vary with the type of work but it is customary to establish them as certain allowable percentages of the actual welding time for definite classes of work.

Arc time, as a percentage of actual welding time, will vary from 30 to 75%, depending on the type of work and handling facilities. An average figure for moderately heavy and large work is approximately 50%. A high percentage of arc time is, in general, an indication of efficiency on the part of the operator and his facilities, but not necessarily of low cost, since a high arc time percentage may be obtained with small diameters of electrode as compared to the larger diameters, whereas the increased deposition rates of the latter result in lower costs in spite of lower arc time. In general, greatest economy can be obtained by using the maximum diameter of electrode permissible for the work.

The use of positioning equipment results in lower costs where the weld is of sufficient size and length and the work is of such a nature that it can be positioned. In general, single pass fillet welds up to and including $^5/_{16}$-in. fillets can be made more economically in the horizontal position on weldments requiring cranes to position. For larger fillets lower cost and

improved appearance are usually obtained by positioning the work Positioning will permit the use of the larger diameters of Class E-6020 and similar types of electrode, with higher deposition rates, as indicated by a comparison of horizontal and flat welding speeds in Tables 7 and 8.

MANUAL METAL ARC-WELDING SPEEDS

Basis for Speeds

The tables of welding speeds included in this section are based on typical deposition rates shown in the included chart for two general types of heavily coated electrode most commonly used and which are classified in A.W.S.-A.S.T.M. Tentative Specifications for Iron and Steel Arc

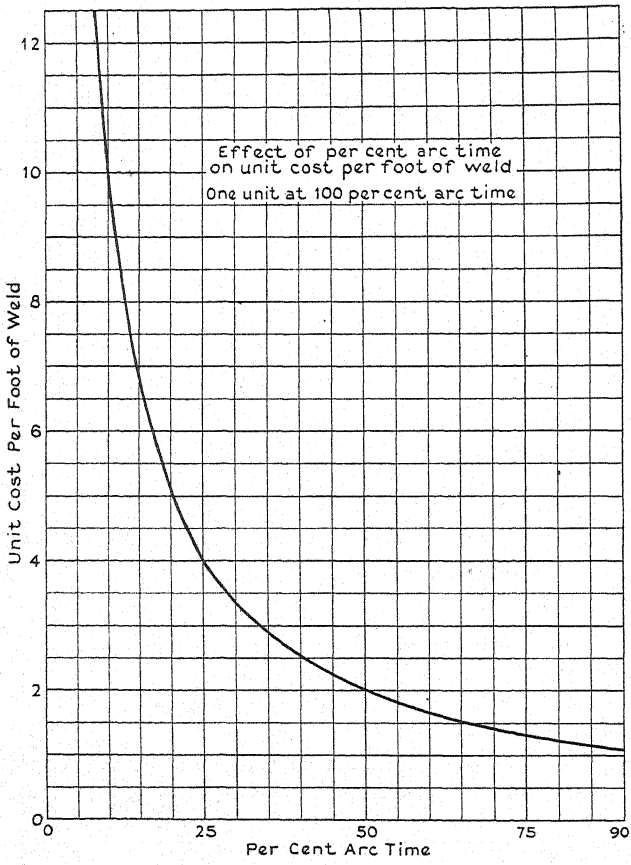


Fig. A

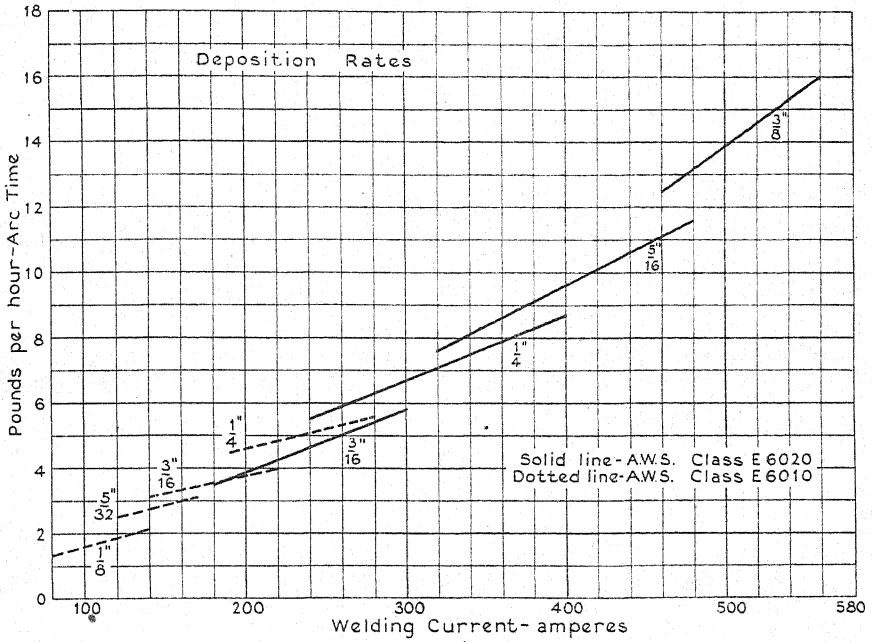

Deposition Rates
Pounds per hour-Arc Time
Welding Current-amperes
Solid line-A.W.S. Class E 6020
Dotted line-A.W.S. Class E 6010
1/8"
5/32"
3/16"
1/4"
5/16"
3/8"
0
2
4
6
8
10
12
14
16
18
100
200
300
400
500
580

Fig. B

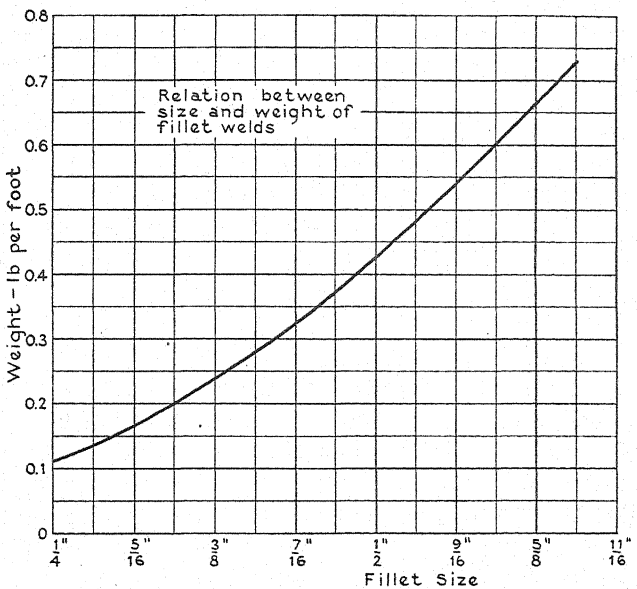

Relation between size and weight of fillet welds
Weight - lb per foot
Fillet Size
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1/4"
5/16"
3/8"
7/16"
1/2"
9/16"
5/8"
11/16"

Fig. C

Welding Electrodes A 233 – 42 T as E-6010 and E-6020. Welding currents given in the tables cover the average ranges which are usually used in industry under the conditions stated. Currents higher than those given may be used, but their use will probably result in physical properties lower than those required for the various classes of electrode.

Classes of Electrode

E-6010. High-quality, reverse polarity, d.c. electrode for all position welding. The a.c.-d.c. straight polarity, all-position electrodes such as E-6011, E-6012 and E-6013 may have deposition rates slightly different than those listed for E-6010 electrode.

E-6020. High-quality, a.c.-d.c. electrode for flat and horizontal fillets. Deposition rates for E-6030 will conform closely to those given for E-6020.

Terms in Which Welding Speeds Are Given

Since conditions and rates vary in different localities, it is impractical to state *costs* per unit length of weld. Therefore all speeds are given in terms of arc time only. Time allowances for changing electrodes, removing slag, handling and positioning the work and personal allowances should be added according to local conditions. Multiplying the total allowed time by the prevailing wage rate will give the cost of the welding.

Size of Welds

Due to the fact that a welding operator cannot always deposit the exact size of fillet weld required, and the minimum size of weld deposited must be equal to that called for on the drawing, the welding speeds given in the tables are based on the fillet legs being 20% oversize on fillets up to and including $^5/_{16}$-in. fillet welds, 10% over on fillets from $^3/_8$ to $^1/_2$ in., inclusive, and 5% over on fillets larger than $^1/_2$ in. Note that if perfect fits are maintained (which will prevent molten metal from running between the joint members) and the welding operator is capable of holding exactly to the fillet size required, then welding speeds higher than those given in the tables can be obtained.

Use of Tables

Example No. 1.—Determine time required to weld 360 in. of $^5/_{16}$-in. horizontal fillet weld with $^1/_4$-in. E-6020 electrode at 300 amps. Assumed arc time, 50%.

1. From Table 7 it will be seen that 5.6 in. per minute (arc time) can be obtained under the above conditions.
2. With 50% arc time the over-all speed will be 2.8 in. per minute.
3. Dividing the 360 in. by 2.8 = 129 min. required.
4. Multiply by the prevailing wage rate to obtain the cost of 360 in. of $^5/_{16}$-in. fillet weld.

Example No. 2.—Determine time required to weld 360 in. of 5/8-in. groove weld in the flat position using the single U preparation with the back side chipped out and welded, using 1/4-in. E-6020 electrode at 320 amperes. Assumed arc time, 50%.

1. From tabulation of "Electrode Requirements for Various Types of Groove Welds," Fig. 8, the amount of deposited metal required per foot of weld for this joint preparation is 1.14 + 0.19 = 1.33 lb. per ft. For 360 in. of weld the weight of deposited metal would be 360/12 × 1.33 = 39.9 lb.

2. From deposition rate curve, Fig. B, the deposition rate for E-6020 electrode at 320 amp. is 7.1 lb. per hour, arc time.

3. With 50% arc time the over-all deposition rate is 3.55 lb. per hour.

4. Dividing 39.9 lb. by 3.55 lb. per hour = 11.2 hr. required.

5. Multiply by the prevailing wage rate to obtain the cost of 360 in. of single U 5/8-in. groove weld.

Table 1—Hand-Welding Speeds—Fillet Welds, Flat and (Horizontal) Positions, Using A.W.S. E-6010 Electrode

Plate Thickness, In.	Elect. Diam., In.	Current Amp.	In. per Minute for Each Size Weld. 100% Duty Cycle. Arc Time Only. No Allowances						
			1 Pass			2 Pass	4 Pass	5 Pass	6 Pass
			3/16	1/4	5/16	3/8	1/2	5/8	3/4
3/16	5/32	130 min.	6.0	3.4	...	...	...	...	...
		160 max.	6.9	3.9	...	...	...	...	...
1/4	5/32	140 min.	6.3	3.5	...	...	...	...	...
		170 max.	7.2	4.1	...	...	...	...	...
	3/16	160 min.	...	...	2.8	2.3	...	...	...
		200 max.	...	...	3.2	2.6	...	...	...
5/16	5/32	140 min.	...	3.5	...	...	...	...	...
		170 max.	...	4.1	...	...	...	...	...
	3/16	160 min.	...	...	2.8	2.3	...	...	...
		200 max.	...	...	3.2	2.6	...	...	...
3/8	3/16	180 min.	...	4.6	3.0	2.5	...	...	...
		200 max.	...	5.0	3.2	2.6	...	...	...
	3/16	180 min.	...	...	...	...	1.4	...	...
		220 max.	...	...	...	...	1.6	...	...
1/2	3/16	180 min.	...	...	3.0	2.5	...	...	...
		200 max.	...	...	3.2	2.6	...	...	...
	3/16	180 min.	...	...	...	...	1.4	...	...
		220 max.	...	...	...	...	1.6	...	...
	3/16 & 1/4	180 / 240 min.	...	...	...	...	...	1.3*	0.93*
	3/16 & 1/4	220 / 280 max.	...	...	...	...	...	1.4*	1.02*
5/8 & up	3/16	180 min.	...	...	...	2.5	...	...	...
		200 max.	...	...	...	2.6	...	...	...
	3/16	180 min.	...	...	...	...	1.4	...	...
		220 max.	...	...	...	...	1.6	...	...
	3/16 & 1/4	180 / 240 min.	...	...	...	...	...	1.3*	0.93*
	3/16 & 1/4	220 / 280 max.	...	...	...	...	...	1.4*	1.02*

(*) First pass 3/16-in., other passes 1/4-in. electrode.

The use of 1/4-in. electrode of Class E-6010 is not generally recommended because greater deposition rates can be obtained with Class E-6020. See Tables 7 and 8.

Table 2—Hand-Welding Speeds—Fillet Welds, Vertical Position Only, Using A.W.S. E-6010 Electrode

Plate Thickness, In.	Elect. Diam., In.	Current, Amp.	In. per Min. for Each Size Weld. 100% Duty Cycle. Arc Time Only. No Allowances							
			1 Pass				2 Pass		3 Pass	
			3/16	1/4	5/16	3/8	3/8	1/2	5/8	3/4
3/16	1/8	90 min.	3.0	...	...	...	...	...	...	...
		120 max.	4.4	...	...	...	...	...	...	...
	5/32	130 min.	...	3.4	2.2	...	...	...	...	...
		150 max.	...	3.7	2.4	...	...	...	...	...
	3/16	160 min.	...	...	2.8	...	...	...	...	...
		180 max.	...	...	3.0	...	...	...	...	...
1/4	1/8	90 min.	3.0	...	...	...	...	...	...	...
		120 max.	4.4	...	...	...	...	...	...	...
	5/32	130 min.	...	3.4	2.2	...	1.8	...	...	...
		150 max.	...	3.7	2.4	...	2.0	...	...	...
	3/16	160 min.	...	...	2.8	2.3	...	...	...	...
		180 max.	...	...	3.0	2.5	...	...	...	...
3/8	5/32	140 min.	...	3.5	2.3	...	1.9	1.0	0.74	...
		160 max.	...	3.9	2.5	...	2.1	1.2	0.82	...
	3/16	160 min.	...	...	2.8	2.3	...	1.3	0.91	...
		180 max.	...	...	3.0	2.5	...	1.4	0.98	...
1/2	5/32	140 min.	...	...	...	...	1.9	1.0	0.74	0.51
		160 max.	...	...	...	...	2.1	1.2	0.82	0.57
	3/16	160 min.	...	...	...	...	...	1.3	0.91	0.64
		180 max.	...	...	...	...	...	1.4	0.98	0.69
5/8 & up	5/32	140 min.	...	...	...	...	1.9	1.0	0.74	0.51
		160 max.	...	...	...	...	2.1	1.2	0.82	0.57
	3/16	160 min.	...	...	...	...	...	1.3	0.91	0.64
		180 max.	...	...	...	...	...	1.4	0.98	0.69

Table 3—Hand-Welding Speeds—Fillet Welds, Overhead Position Only, Using A.W.S. E-6010 Electrode

Plate Thickness, In.	Elect. Diam., In.	Current, Amp.	In. per Minute for Each Size Weld. 100% Duty Cycle. Arc Time Only. No Allowances						
			1 Pass			2 Pass	4 Pass	6 Pass	7 Pass
			3/16	1/4	5/16	3/8	1/2	5/8	3/4
3/16	5/32	130 min.	5.5	3.4	2.1	...	...	...	...
		150 max.	6.0	3.7	2.4	...	...	...	...
1/4	5/32	130 min.	5.5	3.4	2.1	1.8	...	...	...
		150 max.	6.0	3.7	2.4	2.0	...	...	...
	3/16	160 min.	...	...	2.8	...	...	...	...
		180 max.	...	...	3.0	...	...	...	...
3/8	5/32	140 min.	...	3.5	2.2	1.9	1.0	0.74	...
		160 max.	...	3.9	2.5	2.1	1.2	0.82	...
	3/16	160 min.	...	...	2.8	...	1.3	0.91	...
		180 max.	...	...	3.0	...	1.4	0.98	...
1/2	5/32	140 min.	...	...	...	1.9	1.0	0.74	0.51
		160 max.	...	...	...	2.1	1.2	0.82	0.57
	3/16	160 min.	...	...	...	...	1.3	0.91	0.64
		180 max.	...	...	...	...	1.4	0.98	0.69
5/8 & up	5/32	140 min.	...	...	...	1.9	1.0	0.74	0.51
		160 max.	...	...	...	2.1	1.2	0.82	0.57
	3/16	160 min.	...	...	...	...	1.3	0.91	0.64
		180 max.	...	...	...	...	1.4	0.98	0.69

1/2 to 3/4-In. fillets may be made in fewer passes with 3/16-in. electrode than indicated above.

Table 4—Hand-Welding Speeds—Joints Other than Fillet Welds, Flat Position Only, Using A.W.S. E-6010 Electrode

Plate Thickness, In.	Elect. Diam., In.	Current, Amp.	100% Duty Cycle. Arc Time Only. No Allowances	
			Cu. In. per Min.	Lb. per Hr.
1/8	5/32	120 min.	0.15	2.5
		140 max.	0.16	2.7
3/16	5/32	140 min.	0.16	2.7
		170 max.	0.18	3.1
1/4	3/16	180 min.	0.21	3.5
		220 max.	0.24	4.0
3/8	3/16	200 min.	0.22	3.8
		240 max.	0.25	4.2
1/2 & up	1/4	260 min.	0.32	5.4
		300 max.	0.34	5.8

Table 5—Hand-Welding Speeds—Joints Other than Fillet Welds, Vertical and and Overhead Positions Only, Using A.W.S. E-6010 Electrode

Plate Thickness, In.	Elect. Diam., In.	Current, Amp.	100% Duty Cycle. Arc Time Only. No Allowances	
			Cu. In. per Min.	Lb. per Hr.
1/8	5/32	120 min.	0.15	2.5
		130 max.	0.16	2.6
3/16 & up	5/32	130 min.	0.16	2.6
		150 max.	0.17	2.8
	3/16	160 min.	0.19	3.3
		180 max.	0.21	3.6

Table 6—Pounds of A.W.S. E-6010 Electrode Required per Foot of Fillet W eld Including Waste Ends and Spatter Loss

Size of Fillet, In.	Lb. Deposited Metal per Ft. of Fillet Weld	Lb. Electrode Required per Ft. of Fillet Weld
3/16	0.086	0.15
1/4	0.152	0.28
5/16	0.239	0.43
3/8	0.289	0.52
1/2	0.514	0.93
5/8	0.731	1.32
3/4	1.06	1.91

Calculation of Weights.—The above weights of electrode required are based on the sizes of welds as described in the paragraph, "Size of Welds," preceding "Use of Tables." The values given comprise 55% usefully deposited metal, 17% waste ends and 28% spatter (which includes the flux coating) loss.

For pounds of electrode required for joints other than fillet welds see "Electrode Requirements for Various Types of Groove Welds," in this chapter.

Table 7—Hand-Welding Speeds—Horizontal Fillet Welds, Using A.W.S. E-6020 Electrode

Plate Thickness, In.	Elect. Diam., In.	Current, Amp.	In. per Minute for Each Size of Weld. 100% Duty Cycle. Arc Time Only. No Allowances							
			1 Pass			2 Pass	3 Pass	4 Pass	5 Pass	7 Pass
			3/16	1/4	5/16	3/8	7/16	1/2	5/8	3/4
3/16	3/16	180	8.2	4.6	...	....	...	...	...	...
		220	10.0	5.8	...	...	...	...	...	...
1/4	1/4	260	...	7.8	5.0	...	...	...	...	...
		300	...	8.8	5.6	...	...	...	...	...
5/16	1/4	270	...	8.0	5.2	...	...	...	...	...
		300	...	8.8	5.6	...	...	...	...	...
3/8	1/4	270	...	...	5.2	4.2*	3.1	2.4	1.7	1.2
& up		300	...	...	5.6	4.6*	3.4	2.5	1.8	1.3

* The use of a 3/8-in. horizontal fillet weld with E-6020 electrode should be discouraged because of the difficulty in obtaining a good appearing weld. The use of a 5/16-in. fillet with only slightly less strength is to be recommended.

Table 8—Hand-Welding Speeds—Flat Fillet Welds, Using A.W.S. E-6020 Electrode

Plate Thickness, In.	Elect. Diam., In.	Current, Amp.	In. Per Minute for Each Size of Weld. 100% Duty Cycle. Arc Time Only. No. Allowances								
			1 Pass				2 Pass			3 Pass	
			1/4	5/16	3/8	7/16	7/16	1/2	5/8	5/8	3/4
3/16	3/16	190	4.9	...	...	...	...	...	...	...	...
		230	5.9	...	...	...	...	...	...	...	...
1/4	1/4	280	...	5.3	...	...	...	...	...	...	...
		350	...	6.4	...	...	...	...	...	...	...
3/8	1/4	280	...	5.3	...	...	...	...	...	...	...
		360	...	6.6	...	...	...	...	...	...	...
	5/16	380	...	...	6.3	...	...	...	...	...	...
		450	...	...	7.5	...	...	...	...	...	...
1/2 &	1/4	280	...	5.3	...	...	3.2	...	...	...	...
up		360	...	6.6	...	...	4.0	...	...	...	...
	5/16	380	...	...	6.3	...	...	3.5	...	2.5	...
		450	...	...	7.5	...	...	4.2	...	3.0	...
	3/8	480	...	...	9.2	6.7	...	5.1	3.6	...	2.5
		550	...	...	10.9	8.0	...	6.1	4.3	...	3.0

Table 9—Hand-Welding Speeds for Joints Other than Fillet Welds, Using A.W.S. E-6020 Electrode

Plate Thickness In.	Electrode In.	Current, Amp.	100% Duty Cycle. Arc Time Only. No Allowances	
			Cu. In. per Min.	Lb. per Hr.
3/16	3/16	190	0.21	3.6
		230	0.26	4.4
1/4–3/8	1/4	260	0.35	5.9
		360	0.47	7.9
1/2 & up	1/4	280	0.37	6.3
		360	0.47	7.9
	5/16	380	0.53	9.1
		450	0.64	10.8
	3/8	480	0.77	13.2
		550	0.93	15.7

Calculations should be based on proportional volume of each electrode diameter used on joints where small diameters are used for root passes and larger diameters for upper passes of groove welds.

Table 10—Weights of A.W.S. E-6020 Electrode Required for Fillet Welds

Size of Fillet, In.	Lb. Usefully Deposited Metal Required per Ft. of Fillet Weld	Lb. Electrode Required per Ft. of Fillet Weld (Including Scrap Ends and Spatter Loss)
3/16	0.086	0.16
1/4	0.152	0.29
5/16	0.239	0.45
3/8	0.289	0.55
7/16	0.393	0.74
1/2	0.514	0.98
5/8	0.731	1.38
3/4	1.06	2.02

Calculations of Weights.—The above weights of electrode required are based on the sizes of welds as described in the paragraph, "Size of Welds" preceding "Use of Tables." The values given comprise 53% usefully deposited metal, 17% waste ends and 30% spatter (which includes flux coating) loss.

For pounds of electrode required for joints other than fillet welds see "Electrode Requirements for Various Types of Groove Welds," in this chapter.

ELECTRODE REQUIREMENTS FOR VARIOUS TYPES OF GROOVE WELDS

To assist in estimating the approximate weight of various kinds of electrodes needed for various types of welded joints, the following tables have been prepared.

These tables are based on average conditions as outlined below. It should be recognized, therefore, that estimates involving variations from these conditions or from joint preparations as listed in the following pages, necessitate that proper allowances be made accordingly.

The formula used in calculating electrode requirements is as follows:

$$\text{Weight of Electrodes Required} = \frac{\text{Weight of Steel Deposited}}{1 - \text{Electrode Losses}}$$

The weight of steel deposited is calculated from the volume required to fill the joint, plus reinforcement (if used).

Electrode losses, expressed as decimals, are the sum of (*a*) the scrap-end loss plus (*b*) the spatter (which includes the flux coating) losses.

(*a*) For these tables, the scrap-end loss was taken as 17%, which is about average although this value may vary from 10 to 20%, depending on the operator and welding conditions.

(*b*) Likewise, for these tables, spatter and flux-coating losses are considered as 27%.

This may vary between 20 and 35%, depending on the type and size of electrode, welding position, operator's technique, welding current and arc voltage. Excessive current increases spatter loss considerably.

Obviously, in cases where all variables for a specific application are known the electrode requirements calculated directly from the above formula are more accurate than those taken from the tables.

Cost Data for Manual Metal Arc Welding

Square Groove

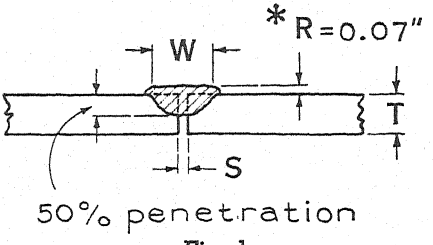
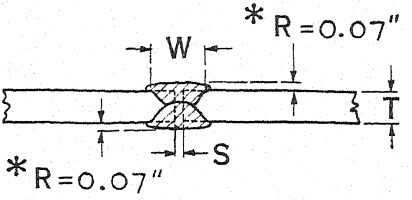


Fig. 1

Inches			Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
			No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	S	Cu. In.	Lb.	Cu. In.	Lb.		
3/16	3/8	0	....	....	0.312	0.088	...	0.16
		1/16	0.071	0.020	0.384	0.109	0.04	0.20
1/4	7/16	1/16	0.094	0.027	0.415	0.129	0.05	0.23
		3/32	0.140	0.039	0.504	0.143	0.07	0.26
5/16	1/2	1/16	0.118	0.033	0.540	0.153	0.06	0.27
		3/32	0.176	0.050	0.600	0.170	0.09	0.30

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Square Groove



If underside of top weld is chipped or flame gouged and welded, add 0.07 lb. to steel deposited (= approx. 0.13 lb. of electrode)

Fig. 2

Inches			Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
			No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	S	Cu. In.	Lb.	Cu. In.	Lb.		
1/8	1/4	0	....	....	0.420	0.119	...	0.21
		1/32	0.047	0.013	0.467	0.132	0.03	0.24
3/16	3/8	1/32	0.071	0.020	0.70	0.199	0.04	0.36
		1/16	0.141	0.040	0.77	0.218	0.07	0.39
1/4	7/16	1/16	0.188	0.053	0.92	0.261	0.10	0.47
		3/32	0.282	0.080	1.02	0.288	0.14	0.53

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Square Groove

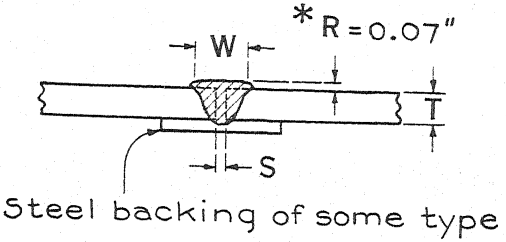


Fig. 3

Inches			Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
			No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	S	Cu. In.	Lb.	Cu. In.	Lb.		
1/8	1/4	0	....	....	0.210	0.060	...	0.11
		1/16	0.094	0.027	0.304	0.086	0.05	0.15
3/16	3/8	1/16	0.140	0.040	0.456	0.129	0.07	0.23
		3/32	0.211	0.060	0.526	0.149	0.11	0.27
1/4	7/16	3/32	0.282	0.080	0.649	0.184	0.14	0.33
		1/8	0.376	0.107	0.742	0.210	0.19	0.38

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

V Groove

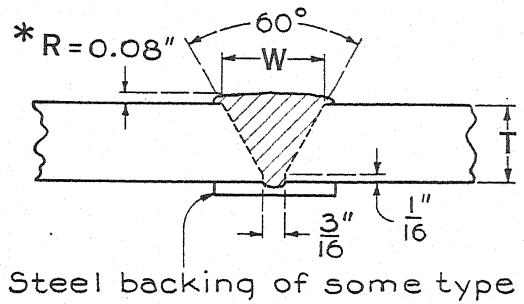


Fig. 4

Inches			Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
			No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	S	Cu. In.	Lb.	Cu. In.	Lb.		
1/4	0.405	3/16	0.815	0.231	1.200	0.340	0.41	0.61
5/16	0.476	3/16	1.14	0.323	1.595	0.452	0.58	0.81

Inches			Amount of Steel Deposited Per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. Per Linear Ft.†	
			No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	S	Cu. In.	Lb.	Cu. In.	Lb.		
3/8	0.549	3/16	1.521	0.432	2.04	0.577	0.77	1.03
1/2	0.693	3/16	2.460	0.696	3.12	0.882	1.25	1.58
5/8	0.838	3/16	3.600	1.020	4.40	1.248	1.82	2.23
3/4	0.982	3/16	4.960	1.405	5.91	1.675	2.50	3.00
1	1.273	3/16	8.350	2.370	9.57	2.710	4.23	4.83

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

V Groove

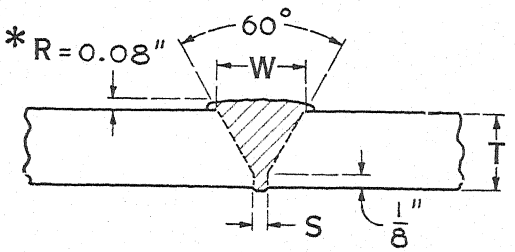


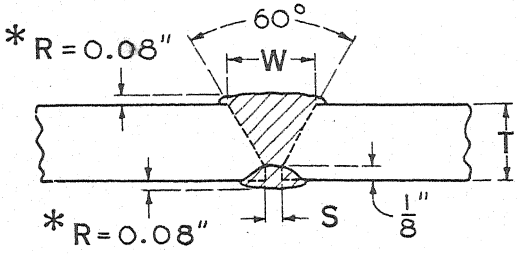
Fig. 5

Inches			Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
			No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	S	Cu. In.	Lb.	Cu. In.	Lb.		
1/4	0.207	1/16	0.300	0.085	0.504	0.143	0.15	0.25
5/16	0.311	3/32	0.611	0.173	0.911	0.258	0.31	0.46
3/8	0.414	1/8	0.995	0.282	1.39	0.394	0.50	0.70
1/2	0.558	1/8	1.730	0.489	2.26	0.641	0.87	1.15
5/8	0.702	1/8	2.660	0.753	3.33	0.942	1.35	1.68
3/4	0.847	1/8	3.840	1.088	4.65	1.32	1.94	2.35
1	1.138	1/8	6.810	1.930	7.90	2.24	3.45	4.00

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Cost Data for Manual Metal Arc Welding

V Groove



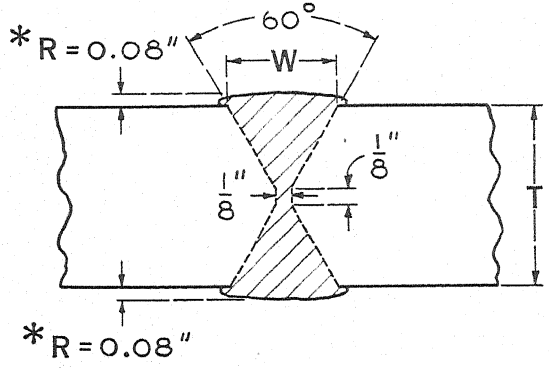
Underside of weld chipped or flame gouged and welded

Fig. 6

Inches			Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
			No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	S	Cu. In.	Lb.	Cu. In.	Lb.		
1/4	0.207	1/16	....	....	0.815	0.231	...	0.41
5/16	0.311	3/32	....	....	1.225	0.346	...	0.62
3/8	0.414	1/8	....	....	1.680	0.475	...	0.85
1/2	0.558	1/8	....	....	2.870	0.811	...	1.45
5/8	0.702	1/8	....	....	3.940	1.115	...	1.99
3/4	0.847	1/8	....	....	5.250	1.490	...	2.66
1	1.138	1/8	....	....	8.500	2.410	...	4.30

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Double V Groove



If underside of top weld is chipped or flame gouged and welded, add 0.10 lb. to steel deposted (equivalent to approx. 0.18 lb. of electrode)

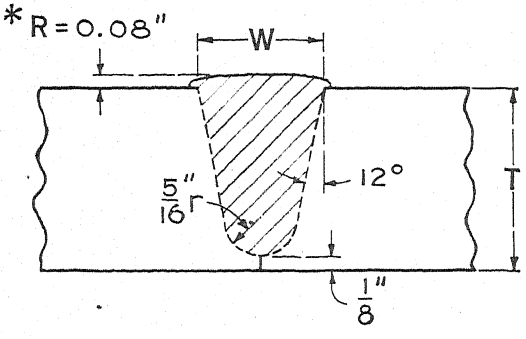
Fig. 7

For Table See Next Page

Inches T	Inches W	Amount of Steel Deposited per Linear Ft. — No Reinforcement Cu. In.	No Reinforcement Lb.	With Reinforcement* Cu. In.	With Reinforcement* Lb.	Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.† — No Reinforcement	With Reinforcement*
5/8	0.405	1.775	0.502	2.56	0.724	0.90	1.29
3/4	0.468	2.410	0.682	3.31	0.937	1.22	1.68
1	0.630	4.150	1.175	5.36	1.52	2.10	2.71
1 1/4	0.774	6.27	1.775	7.75	2.19	3.17	3.92
1 1/2	0.919	8.85	2.495	10.59	3.00	4.45	5.35
1 3/4	1.063	11.80	3.335	13.82	3.91	5.95	6.98
2	1.207	15.20	4.30	17.58	4.97	7.68	8.88
2 1/4	1.352	19.00	5.38	21.65	6.12	9.60	10.95
2 1/2	1.496	23.30	6.60	26.20	7.40	11.80	13.20
3	1.784	33.00	9.35	36.50	10.33	16.70	18.50
3 1/2	2.073	44.70	12.65	48.70	13.80	22.60	24.60
4	2.368	58.15	16.45	62.80	17.80	29.40	31.70

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

U Groove



If underside of weld is chipped or flame gouged and welded, add 0.19 lb. to steel deposited (equivalent to approx. 0.34 lb. of electrode)

Fig. 8

Inches T	Inches W	Amount of Steel Deposited per Linear Ft. — No Reinforcement Cu. In.	No Reinforcement Lb.	With Reinforcement* Cu. In.	With Reinforcement* Lb.	Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.† — No Reinforcement	With Reinforcement*
1/2	0.652	2.325	0.659	2.95	0.835	1.18	1.49
5/8	0.705	3.345	0.947	4.02	1.14	1.70	2.04
3/4	0.758	4.435	1.255	5.17	1.46	2.24	2.61
1	0.865	6.870	1.945	7.70	2.18	3.47	3.89
1 1/4	0.971	9.62	2.72	10.60	3.00	4.86	5.35
1 1/2	1.077	12.66	3.59	13.72	3.89	6.41	6.95
1 3/4	1.173	16.00	4.53	17.10	4.84	8.08	8.65
2	1.292	19.75	5.60	21.04	5.96	10.00	10.65

Inches		Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
		No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	Cu. In.	Lb.	Cu. In.	Lb.		
2 1/4	1.396	23.80	6.75	25.20	7.12	12.05	12.75
2 1/2	1.502	28.20	7.98	29.65	8.40	14.25	15.00
2 3/4	1.608	32.80	9.29	34.65	9.73	16.60	17.40
3	1.715	37.80	10.70	39.45	11.19	19.10	20.00
3 1/2	1.927	48.60	13.80	50.50	14.30	24.70	25.50
4	2.140	61.00	17.30	63.10	17.90	30.90	31.90

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Modified U Groove

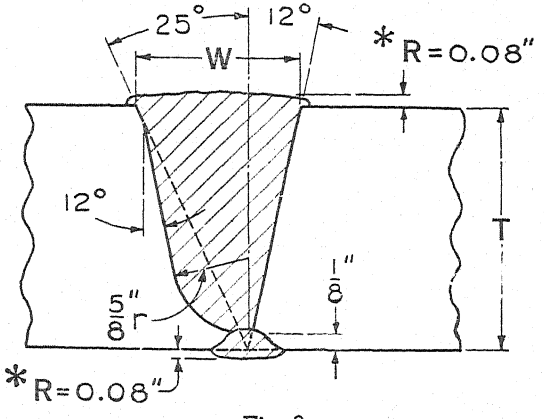


Fig. 9

For irregular shapes, preparation of the modified U groove is usually more economical than the regular U groove (Fig. 8).

Approximately 5% more electrode must be used to fill the joint than for the regular U groove.

Double U Groove

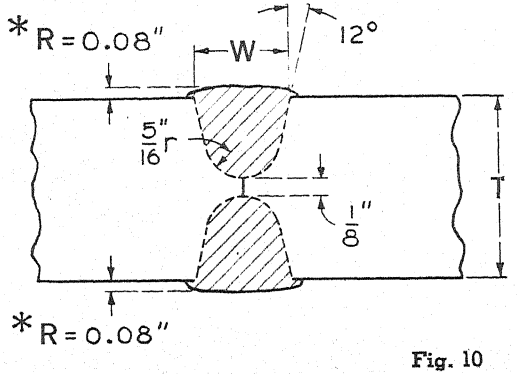


Fig. 10

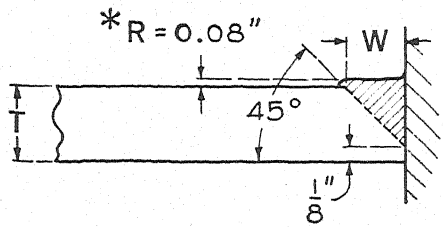
If underside of top weld is chipped or flame gouged and welded, add 0.19 lb. to steel deposited (equal to approx. 0.34 lb. of electrode)

For Fig. See Previous Page

Inches		Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft †	
		No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	Cu. In.	Lb.	Cu. In.	Lb.		
1	0.685	5.64	1.60	6.96	1.98	2.86	3.54
1 1/4	0.731	7.75	2.19	9.15	2.59	3.91	4.62
1 1/2	0.784	10.00	2.83	11.55	3.27	5.05	5.83
1 3/4	0.838	12.47	3.53	14.10	3.99	6.30	7.12
2	0.891	15.08	4.26	16.74	4.74	7.60	8.46
2 1/4	0.944	17.80	5.04	19.60	5.55	9.00	9.90
2 1/2	0.977	20.70	5.85	22.60	6.41	10.45	11.45
2 3/4	1.050	23.80	6.73	25.80	7.30	12.00	13.05
3	1.103	27.15	7.75	29.40	8.34	13.85	14.90
3 1/2	1.211	33.98	9.61	36.30	10.30	17.20	18.40
4	1.316	41.55	11.75	44.00	12.50	21.00	22.30

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Single Bevel T



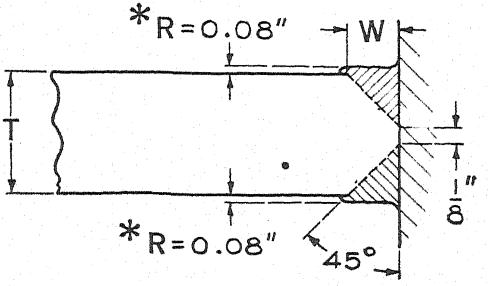
If underside of weld is chipped or flame gouged and welded, add 0.19 lb. to steel deposited (approx. equal to 0.34 lb. of electrode)

Fig. 11

Inches		Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
		No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	Cu. In.	Lb.	Cu. In.	Lb.		
1/4	0.125	0.096	0.027	0.216	0.061	0.05	0.10
5/16	0.188	0.216	0.061	0.396	0.112	0.11	0.20
3/8	0.250	0.372	0.106	0.611	0.173	0.19	0.31
1/2	0.375	0.840	0.238	1.211	0.343	0.43	0.61
5/8	0.500	1.500	0.425	1.980	0.560	0.76	1.00
3/4	0.625	2.340	0.663	2.950	0.835	1.19	1.50
1	0.875	4.590	1.303	5.57	1.575	2.33	2.81

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Double Bevel T



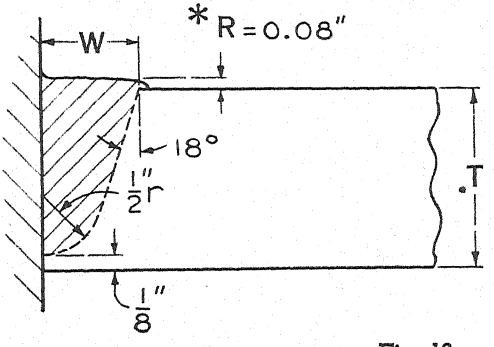
If underside of top weld is flame gouged or chipped out and welded, add 0.19 lb. steel deposited (approx. equal to 0.34 lb. of electrode)

Fig. 12

Inches		Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
		No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	Cu. In.	Lb.	Cu. In.	Lb.		
1/2	0.188	0.42	0.120	0.78	0.221	0.22	0.39
5/8	0.250	0.756	0.213	1.238	0.350	0.38	0.62
3/4	0.313	1.175	0.332	1.775	0.503	0.59	0.90
1	0.438	2.294	0.648	3.130	0.886	1.16	1.58
1 1/4	0.563	3.790	1.076	4.870	1.38	1.92	2.46
1 1/2	0.688	5.670	1.607	7.00	1.98	2.87	3.54
1 3/4	0.813	7.92	2.245	9.47	2.68	4.01	4.78
2	0.938	10.53	2.985	12.33	3.50	5.33	6.25

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

J Groove



If underside of weld is chipped or flame gouged and welded, add 0.19 lb. to steel required (equal to approx. 0.34 lb. of electrode)

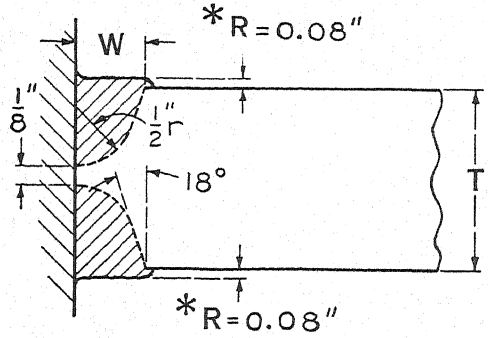
Fig. 13

For Table See Next Page

Inches		Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
		No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	Cu. In.	Lb.	Cu. In.	Lb.		
1	0.625	5.03	1.43	5.64	1.60	2.65	2.85
1 1/4	0.719	7.20	2.04	7.91	2.24	3.64	4.00
1 1/2	0.781	9.46	2.69	10.20	2.80	4.80	5.15
1 3/4	0.875	12.12	3.43	12.95	3.67	6.12	6.55
2	0.969	14.63	4.15	15.60	4.41	7.40	7.87
2 1/4	1.031	17.75	5.03	18.35	5.19	9.00	9.42
2 1/2	1.094	20.90	5.92	21.95	6.21	10.60	11.10
2 3/4	1.188	24.35	6.90	25.55	7.23	12.30	12.92
3	1.281	28.10	7.95	29.30	8.29	14.20	14.80
3 1/2	1.438	36.30	10.30	37.80	10.70	18.40	19.10
4	1.594	45.40	12.90	47.00	13.30	23.00	23.70

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Double J Groove



If underside of top weld is chipped or flame gouged and welded, add 0.19 lb. to steel deposited (equivalent to approx. 0.34 lb. of electrode)

Fig. 14

Inches		Amount of Steel Deposited per Linear Ft.				Weight of Heavily Coated Electrode Required in Lb. per Linear Ft.†	
		No Reinforcement		With Reinforcement*		No Reinforcement	With Reinforcement*
T	W	Cu. In.	Lb.	Cu. In.	Lb.		
1	0.500	3.71	1.05	4.67	1.33	1.87	2.37
1 1/4	0.563	4.92	1.39	6.00	1.70	2.48	3.03
1 1/2	0.594	6.95	1.97	8.10	2.29	3.52	4.08
1 3/4	0.625	8.63	2.45	9.83	2.79	4.37	5.00
2	0.656	10.80	3.06	12.06	3.42	5.47	6.11
2 1/4	0.688	12.97	3.67	14.29	4.04	6.55	7.21
2 1/2	0.750	15.12	4.28	16.68	4.69	7.65	8.38
2 3/4	0.781	17.52	4.95	19.00	5.38	8.85	9.60
3	0.813	19.82	5.62	21.45	6.08	10.10	10.85
3 1/2	0.906	25.05	7.12	26.80	7.58	12.70	13.55
4	0.969	31.05	8.78	32.80	9.28	15.70	16.60

* R—Height of reinforcement.
† Includes scrap end and spatter loss.

Table 11—Cost Data for Manual Oxyacetylene Welding

Thickness of Steel, In.	Ga.	Joint Preparation (Spacing Zero)	Diam. of Rod, In.	Tip Size Use Tip Consuming This Volume of Acetylene Per Hr.	Material Requirements: Oxygen, Cu. Ft. Per Hr.	Oxygen, Cu. Ft. Per Linear Ft. Welded	Acetylene, Cu. Ft. Per Hr.	Acetylene, Cu. Ft. Per Linear Ft. Welded	Rod, Lb. Per Hr.	Rod, Lb. Per Ft.	Speeds: In. per Min.	Speeds: Ft. per Hr.
1/64	28	Square groove	...	0.2– 0.7	0.7	0.03	0.7	0.03	.....	...	5.2-6.0	26.0–30.0
1/32	22	Square groove	...	0.6– 1.6	1.0	0.05– 0.04	1.0	0.05– 0.04	.....	...	4.4–5.0	22.0–25.0
1/16	16	Square groove	1/16	1.0– 3.2	2.4	0.13– 0.11	2.3	0.13– 0.11	0.23–0.27	0.013	3.6–4.2	18.0–21.0
3/32	13	Square groove	3/32	2.0– 7.0	5.1	0.36– 0.30	4.9	0.36– 0.29	0.42–0.51	0.030	2.8–3.4	14.0–17.0
1/8	11	Square groove	1/8	3.0– 12.0	8.8	0.80– 0.68	8.5	0.77– 0.65	0.58–0.69	0.053	2.2–2.6	11.0–13.0
3/16	7	90° Single V	3/16	6.0– 22.0	17.7	2.36– 2.08	17.0	2.27– 2.00	1.13–1.28	0.150	1.5–1.7	7.5– 8.5
1/4	3	90° Single V	3/16	10.0– 35.0	27.0	4.50– 3.86	26.0	4.33– 3.72	1.59–1.86	0.265	1.2–1.4	6.0– 7.0
5/16	0	90° Single V	1/4	25.0– 40.0	33.0	7.40– 6.05	32.0	7.11– 5.82	1.87–2.28	0.414	0.9–1.1	4.5– 5.5
3/8	3/0	90° Single V	1/4	30.0– 50.0	45.7	11.42– 9.13	44.0	11.0 – 8.80	2.39–2.98	0.597	0.8–1.0	4.0– 5.0
1/2	7/0	60° Single V	1/4	35.0– 65.0	58.2	11.65– 9.70	56.0	11.2 – 9.33	2.90–3.48	0.637	1.0–1.2	5.0– 6.0
5/8	...	60° Single V	5/16	45.0– 85.0	73.8	21.10–16.42	71.0	20.30–15.79	3.06–3.92	0.872	0.7–0.9	3.5– 4.5
3/4	...	60° Single V	5/16	60.0–105.0	91.5	36.60–26.16	88.0	35.20–25.17	3.27–4.57	1.307	0.5–0.7	2.5– 3.5

FACTORS AND DATA INVOLVED IN ESTIMATING COSTS FOR MANUAL OXYACETYLENE WELDING

The quality and quantity of welding produced by manual oxyacetylene operations is dependent upon the skill and experience of the operator, a fact common to all hand operations. The work of the novice is slow and of doubtful quality. With increased practice and experience these factors are improved. If an operator works solely on one problem he will ultimately develop a high degree of skill which when compared with other operations, by less skilled men, will indicate production speeds of very high order. Therefore, in publishing data for cost estimating it becomes necessary to establish average conditions with the full realization that considerable variations will be encountered under actual working conditions.

The data given in Table 11 represent values obtainable with average operators employing single flame tips. The governing conditions are set forth in the table. Actual job conditions have been assumed for this tabulation, hence allowance has been made for lost time, etc. It must be realized that the multitude of variables influencing manual oxyacetylene welding render it impossible to set definite values on the speed of welding and consequently on the amounts of oxygen, acetylene and rod. Therefore, ranges are indicated for these factors. Obviously the slower speeds represent less experienced operators and involve higher gas consumption while the higher speeds apply to the opposite conditions. The only definite values provided are for pounds of rod deposited per foot of weld which figures are reasonably constant. The data on welding rod consumption assume weld reinforcements equivalent to about 25% of base metal thickness.

To avoid proprietary references tip sizes have been expressed in terms of acetylene flow per hour. The governing factor in oxyacetylene welding is the cubic feet of acetylene required to deposit one pound of weld metal, hence this is the logical method for establishing proper tip sizes for given thicknesses. Data on acetylene flows for each tip size are generally available from equipment manufacturers.

CHAPTER 36A

BUILDINGS*

Specifications, Materials and Procedures, Design of Frame, Design of Connections, Calculation of Weld Stresses, Types of Joints, Seats and Brackets, Wind Connections, Columns, Girder Design, Truss Design, Tolerances, Erection and Field Welding, Inspection

Specifications

FOR the control of welding, when it is employed in the fabrication and construction of steel frame buildings, the AMERICAN WELDING SOCIETY has adopted and issued a Code for Arc and Gas Welding in Building Construction—1941 Edition. This Code deals primarily with the welding, *per se.*

The American Institute of Steel Construction's Specification for the Design, Fabrication and Erection of Structural Steel for Buildings by Arc and Gas Welding accepts the provisions of this Code which governs all of the features relating to the use of welding. As the title implies, this Specification provides for the design, fabrication and erection of the structure as a whole.

These two documents provide, for the benefit of building officials, designers and constructors, a complete and authoritative coverage of the recognized best practice in the design and construction of steel building frames. Engineers, concerned with the construction of steel buildings on which welding is employed, should be familiar with both of them.

Materials and Procedures

Structural steel for buildings, as specified by the A.W.S. Code and covered by the A.I.S.C. Specification, must conform to the American Society for Testing Materials Standard Specification Serial Designation A7. This steel is of proved weldability and is practically the only grade used in building construction.

At the present time, welding in building construction is almost always performed manually by the metal arc process. Occasionally gas welding is used and, together with the more commonly used metal arc process, is given

* Prepared by a committee consisting of T. R. Higgins, American Institute of Steel Construction, *Chairman;* F. H. Dill, American Bridge Co.; LaMotte Grover, Air Reduction Sales Co.; M. P. Korn, Consulting Engineer; H. W. Lawson, Bethlehem Steel Co.; H. H. Moss, The Linde Air Products Co.; A. Vogel, General Electric Co.

a prequalified status in the A.W.S. Code and A.I.S.C. Specification when performed in accordance with the provisions thereof. The character of the work involved in building construction is ordinarily such as to offer little inducement to the use of automatic welding equipment. Should such a process be deemed desirable, qualification tests would be required.

Some progress has been made in the use of resistance welding to join component parts of built-up sections, but the number of structural shops equipped to weld by the resistance welding process is very limited. Obviously, qualification of this procedure requires different tests than are prescribed under the A.W.S. Standard Qualification Procedure. At the same time it should be pointed out that the relative importance of welds used merely to stitch together component parts as compared with those used to carry calculated stress, and the relatively low stresses involved under actual service conditions, will enter into the consideration where the use of this process is proposed for the joining of component parts under conditions that involve no transfer of calculable stress.

Design of Frame

Prior to the design of a steel building frame, it is first necessary to make certain assumptions as to the behavior of the joints. In the design of these joints, therefore, it is necessary to insure that their actual behavior under loading will conform to these prior assumptions. Thus, if the frame is proportioned to support the loads as a "rigid-frame," in which the distribution of stress is predicated upon the elastic behavior of the frame, the joints must function without sensible angular distortion.

The ordinary assumptions used in the design of building frames, and the joint behavior on which these assumptions are based, are:

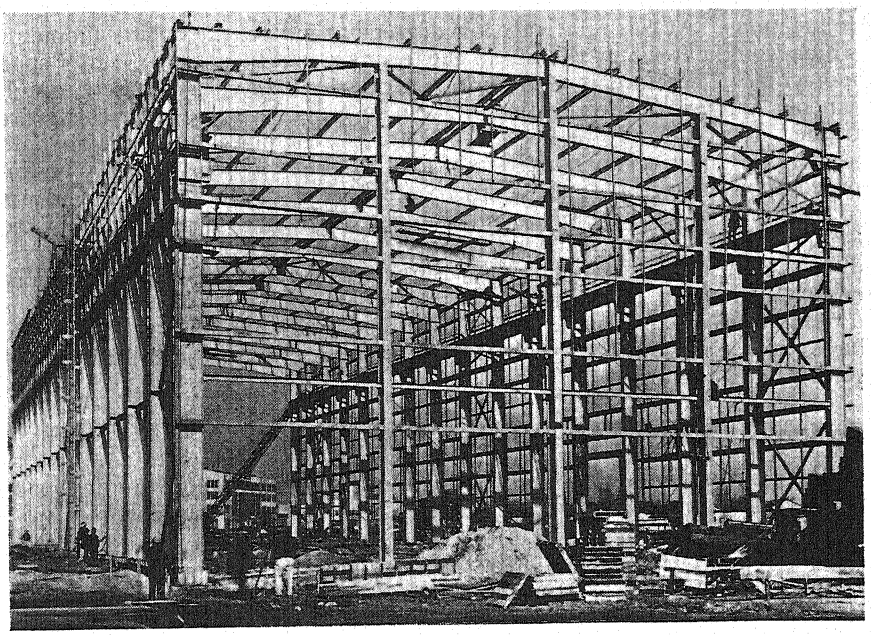
1. "Rigid-frame" construction, in which the joints, under loaded condition, undergo no sensible angular distortion. Under this assumption the maximum moments for which the members are proportioned may be, and usually are, substantially smaller than in the case of
2. "Flexible," or "simple span and column" construction, in which no attempt is made to restrain the ends of beams with connections offering any predictable amount of resistance to angular distortion and in which, therefore, the beams are proportioned to resist the full bending moment associated with simple span loading.

Due to the resulting homogeneity of the completed work, welding is particularly well suited to rigid-frame construction. It also offers the advantages of (1) a compactness of joint with an attendant saving in connection material and (2) a simplicity of joint which, if the steel work is left exposed to view, enhances the general appearance of the building interior. Because of these advantages, it is in the rigid-frame type of structures that welding has been most effectively used in building construction.

However, the work involved in a rigid-frame analysis to determine the maximum stresses occurring at the several joints under all reasonable conditions of loading, has discouraged any general use of this type of construction except where the framing system is relatively simple. This condition continues in spite of the fact that saving of material can be achieved through the utilization of continuity and in spite of the simplification that has been brought about in the mathematics of rigid-frame solutions.

The design of tier buildings is, therefore, most frequently executed on the assumption of simple span beams. When such design assumptions are made, the joints must be (1) sufficiently flexible, while carrying the vertical reactions, to accommodate the end rotations associated with simple span deflections, or (2) sufficiently strong to resist, with safety to the welds, *any* induced moment that might be imposed upon them as a result of their inherent stiffness.

The treatment of connections required to resist side sway, resulting from an empirical distribution of wind moments on tier buildings not designed as elastic frames, is given under the heading of Wind Connections. It is not the purpose of this chapter to attack or defend the resort to empirical



Welded Rigid Frame Factory Type Building

methods in the design for wind on steel frame buildings. Suffice it to say that there is a preponderance of evidence that the methods have given entirely satisfactory results and, at the present, they enjoy wide popularity.

Not infrequently the design of a building frame involves a combination of the rigid and flexible types of construction. Thus, one or more lines of beams may be proportioned on the condition of continuity in an otherwise flexible type of framing. Or minor framing may be attached with flexible connections to an otherwise rigid frame. The designing engineer, therefore, must (1) show on his design drawings the type or types of connections that are required, or (2) clearly indicate on his drawings the types of construction contemplated and the extent of each type. In the latter case, assuming that the shop drawings are to be made by others, he must be prepared to give the detailer all necessary stress and loading data required for the

design of the connections and must be responsible for the adequacy and fitness of the connections designed in accordance with these data.

Possibility of a third type of construction, employing somewhat different design assumptions, is suggested by the work of Messrs. Johnston and Mount at Lehigh University.* In this type of construction, the joints employed would be semi-rigid. Through prior investigation, however, the amount of rotation produced by varying moment applications upon each joint would be known. With a series of proved joints available, the designer might realize a high proportion of the saving in main framing material, made possible through continuity, by proportioning the members on the assumption that the joints employed would develop not less than the specified degree of rigidity—possibly 50% for the seat and top angle type of connections. At this relatively low degree of rigidity, the critical moments which would determine the size of the beams would be positive, center span moments. Therefore, it would not be necessary to make a complete, simultaneous analysis of the effects of a given system of loading upon the entire frame. It would only be necessary, in proportioning a single member, to assume the most severe condition of loading that might reasonably be imposed upon the member; the indirect contribution of more remote elements of the frame in assisting the member under consideration in sustaining the loading could be ignored since it would be small and would tend only to reduce the critical positive moment. Further research work to develop more complete data on joints which would implement the design assumptions for this type of construction will be watched with interest by those who have long recognized the inherent contribution of these joints to the strength of the frame.

Design of Connections—General Considerations

There are a number of factors that have a bearing upon the design of welded connections in building frames besides those already discussed.

In the first place the amount of welding required per ton of finished work is relatively low as compared with the product of many other steel fabricating industries. Hence, it is obvious that the handling costs are relatively high and that careful attention to this factor is likely to yield economies fully as significant as any that may derive from the execution of the welding itself.

Greater economy is generally achieved if as much of the assembling and welding as possible are performed in the shop where a better opportunity is afforded for the use of jigs and clamping devices, and where the work can be positioned to the best advantage for welding. In the design of all connections, whether shop or field welded, it is important to keep in mind the access of the operator to the welding that must be done. His ability to make good welds is directly related to the convenience of the position he must take while welding. In the field, the excessive use and adjustment of staging can become a considerable item of expense; in actual practice much of the field welding on well-planned work is performed by operators seated or standing on the steel frame, without the assistance of staging. Some-

* See "Designing Welded Frames for Continuity," by Bruce Johnston and E. H. Mount in *The Welding Journal* for October 1939; also "Analysis of Building Frames with Semi-Rigid Connections," by the same authors, in the March 1941 *Proceedings of the American Society of Civil Engineers.*

times welding operators work from seats supported by light stirrups hooked over steel floor beams and so constructed as to allow some adjustment. It is well for the designer and detailer to keep this picture in mind, and where conditions will permit, arrange the welding for a particular connection so that it may be performed with a minimum of shifting around.

Until recently fillet welds were used almost exclusively where welding was employed in the fabrication and erection of building frames. While it is probably true that considerably more weld metal is still deposited as fillet welds than as butt welds, in the fabrication of structural steel, a notable development in the past few years has been the increasing use of butt welds.

Earlier preference for the fillet type may be explained by the fact that, to insure accurate work in riveted fabrication, the industry had always directed its attention to the accurate location of the rivet holes. A relatively large tolerance at the edges of parts, of no particular significance in riveted work but much too large to insure an accurate fit-up for butt welds, was generally accepted. The principle of lapping plates, dictated by the nature of riveted work and suggesting the use of fillet type welds, had become deeply rooted—both in shop and erection practice.

Recent investigation of the behavior of welded joints subjected to fatigue loading would seem to favor the use of butt rather than fillet welds. Yet, in most building frames fatigue loading, which may be defined as the reversal, or substantial unloading, of stress many thousands of times, seldom is encountered. Hence it would seem that the difference of opinion as to the relative merit of fillet-welded joints, usually requiring some connecting material, and direct, butt-welded joints, requiring closer edge tolerances, may in building construction eventually be resolved on the basis of comparative over-all costs rather than on performance.

Calculation of Weld Stresses

Allowable working stresses for welds are generally given in codes and specifications in pounds per square inch of effective throat area. However, calculations for the proportioning of fillet and butt welds in design

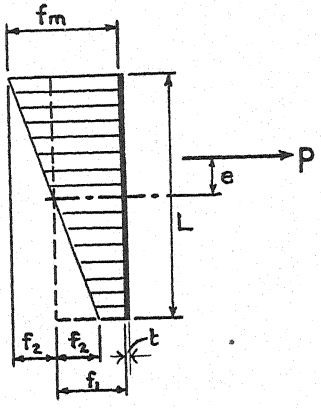


Fig. 1

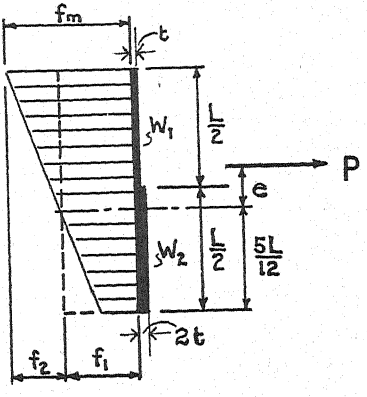


Fig. 2

work are much simplified by the usual practice of expressing weld stresses in terms of pounds per linear inch of weld.

Where a weld or a group of welds is subject to both direct stress and torsion or bending the maximum combined stress is determined on the basis of the usual assumptions relating to stress distribution as affected by the disposition of each element about the centroid of the group.

In Fig. 1 a single weld, of fillet or butt type, having a throat, t, is carrying the load, P, applied at a distance, e, from the centroid of the weld. The resulting maximum unit weld stress, f_m, is the sum of the unit stresses, f_1 and f_2, produced by the direct load and the torsion (bending moment created by the eccentricity), respectively, and may be expressed as,

$$f_m = f_1 + f_2 = \frac{P}{A} + \frac{Pe}{S} = \frac{P}{Lt} + \frac{Pe}{{}^1/_6\, L^2\, t}$$

in which A is the throat area and S is the section modulus of the throat area. The resulting maximum unit stress, f_m, which is given in pounds per unit area, must be multiplied by t if the more common pounds-per-linear-inch basis is to be used. Thus, the resulting maximum stress per linear inch of weld, $f_m t$, is equal to $\frac{P}{L} + \frac{6Pe}{L^2}$ and, conversely the throat size, t, of a single weld of length, L, loaded as in Fig. 1 may be expressed as $\frac{1}{f_m}\left(\frac{P}{L} + \frac{6Pe}{L^2}\right)$, where f_m is the maximum allowable unit stress in pounds per square inch of throat area.

The relative significance of each weld in an eccentrically loaded group is deemed proportionate to its throat.

In Fig. 2, the throat of W_1 is t and that of W_2 is $2t$. The maximum unit stress may be expressed,

$$f_m = f_1 + f_2 = \frac{P}{A} + \frac{Pe}{S} = \frac{P}{{}^3/_2 Lt} + \frac{Pe}{{}^{11}/_{56} L^2 t}$$

and $f_m t$ (maximum stress per inch of weld) $= \frac{2P}{3L} + \frac{56Pe}{11L^2}$.

The value $\frac{11L^2t}{56}$ for S, applicable to the upper end of the composite weld where maximum stress occurs, is obtained in the same manner as the section modulus of the cross-sectional area of a beam or column.

If the load, P, in Fig. 2 were applied at a distance, e, below the centroid of the composite weld, instead of above it, the resulting maximum stress per unit area would be,

$$f_m = \frac{P}{A} + \frac{Pe}{S} = \frac{P}{{}^3/_2 Lt} + \frac{Pe}{{}^{11}/_{40} L^2 t}$$

Note that the maximum stress now occurs at the lower end of the composite weld and that the applicable value for S, obtained in the same manner as for the cross-section of a beam or column, is now $\frac{11L^2t}{40}$.

The resulting maximum stress in pounds per linear inch of weld would be $2f_m t$ or $\frac{4P}{3L} + \frac{80Pe}{11L^2}$.

The direction of loading in Figs. 1 and 2 is such that the direct and torsional stresses are parallel and, hence, directly additive. In Fig. 3, however, the torsional stress acts upon the plane of the weld throat in a direction normal to that of the direct stress. The resulting maximum combined unit stress, f_m, under this condition is usually assumed as equal to $\sqrt{f_1^2+f_2^2}$. This assumption generally is made for both fillet and butt welds, although, in the case of butt welds, possibly the more involved expression for principal stress, $f_m = \frac{f_2}{2} + \sqrt{f_1^2 + \left(\frac{f_2}{2}\right)^2}$, is more nearly correct even though it gives slightly higher values for f_m. In the case of fillet welds any stress on the throat of the weld, regardless of direction, is treated as a shearing stress and is limited to 13,600 psi.

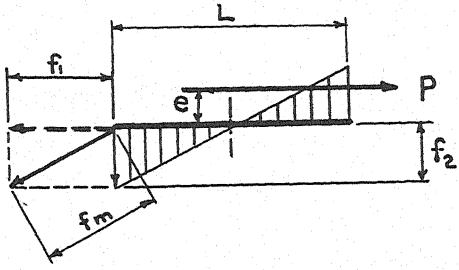


Fig. 3

Tension stresses up to 16,000 psi. are permitted by the A.W.S. Code on the throat of butt welds. Compression and shearing stresses are permitted, on the throat of butt welds, up to the limiting values, prescribed for compression and shear, respectively, for the base metal. If in Fig. 3, f_1 is the unit shearing stress on the throat of a butt weld, and f_2 is the maximum unit tension stress produced on the weld throat by the eccentric loading, f_1 must not exceed the allowable unit working stress for shear in the base metal (given as 13,000 psi. in practically all codes and design specifications) while the resultant combined (vector) stress must not exceed the limit for tension stress, or 16,000 psi.

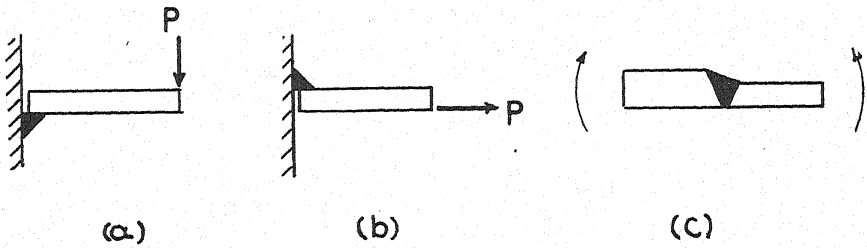


Fig. 4

Joints such as are illustrated in Fig. 4, which are welded from one side only, should not be subject to bending about the longitudinal axis of the weld because such loading creates very high stress concentrations at the

root of the weld. Joints of this sort may be used only where other parts of the structure prevent bending or rotation, of the character indicated by the loading on the sketches. The use of flexible or semi-rigid angles for the top flange connection of beams is a permitted exception to this rule. Both of these applications have been carefully investigated by tests and found entirely safe within the limits of intended use.

Types of Joints

Because of the greater freedom afforded the designer of welded connections by the nature of welded fabrication, classification of connections into a relatively few standard types would not only be difficult but undesirable except possibly in the case of the flexible types such as those shown in Fig. 6. In rigid-frame construction particularly, the variety of forms and wide range in stresses to be carried recommend careful attention to the design of each joint.

Figure 5 shows some of the types of joints frequently used in rigid frames. It is not intended to imply that these are the only satisfactory solutions; their inclusion in this chapter is for the purpose of illustrating the following points, recognition of which is necessary to obtain the best results:

1. Foremost of the precepts which could be laid down is the rule that the simplest and most straightforward treatment of the problem will produce the most satisfactory results with the least cost.
2. While the use of curved work at joints may be justified on aesthetic grounds, it usually tends to increase the fabricating costs.
3. It is better to keep the number of component parts in a joint at a minimum, using comparatively heavy material if necessary to avoid the introduction of reinforcing plates and elaborate stiffener systems.
4. The intensity of web shear should be investigated as well as the flange stresses at a joint.
5. Where a beam frames directly to a column flange, the transverse welds across the column flange, transferring the stresses from the beam flanges to the column, should be backed up by stiffener plates, welded to the column web and to the column flange to which the beam is attached.

Two general types of flexible beam-to-column connections, which are commonly used where beams frame at right angles to a column flange or web, are illustrated in Fig. 6. Both types offer little resistance to the rotation of the end of the beam caused by its deflection under simple span loading. In the seated type the top angle will deform without injury to the welds attaching it to the column and the beam. In the framed type, (c), the upper half of the outstanding legs of the web angles will accomplish the same purpose, although with slightly higher stresses in the angle and the welds at the toe of the outstanding legs. Investigation* has demonstrated that, within the limits required for the simple-span deflection of beams on moderate spans, neither the angles nor the welds suffer any damage from the plastic deformation which admittedly must take place to accommodate the rotation. (Note that the only function of the top angle of the seated type is to provide lateral support for the beam until such time as the floor or roof slab or deck has been installed.) The angle sizes shown are for moderate spans, say, up to 24 ft.

* See "Flexible Welded Angle Connections," by Bruce Johnston and Lloyd F. Green, *The Welding Journal*, October 1940.

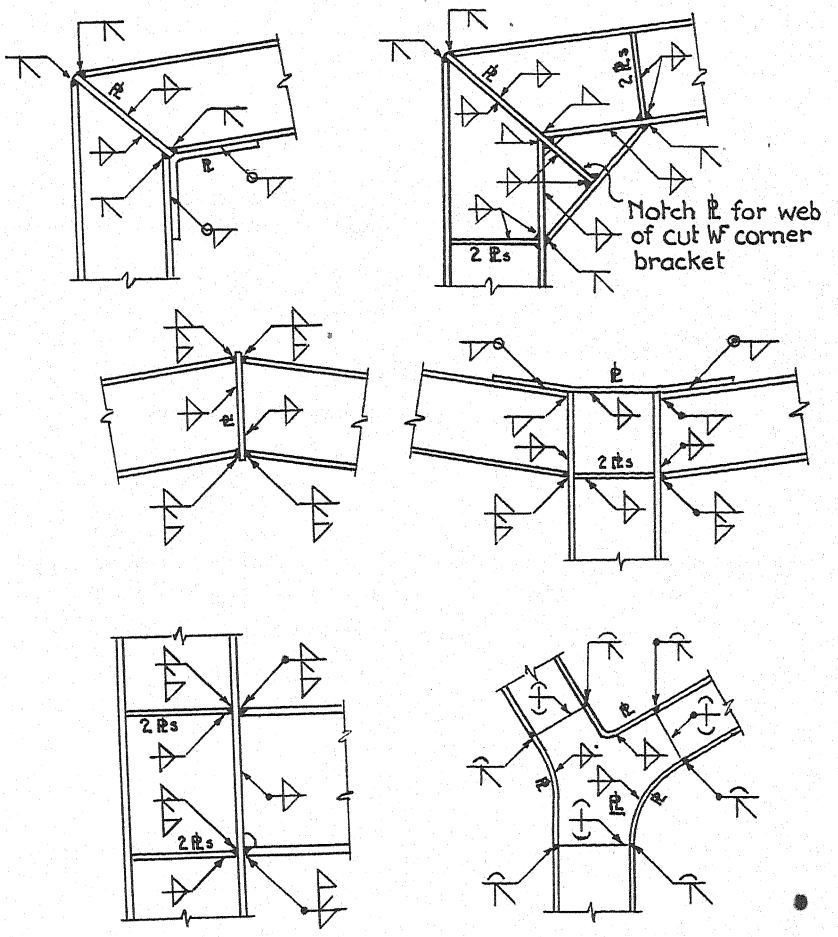

Notch ℄ for web of cut WF corner bracket
2 ℄s
2 ℄s
2 ℄s
2 ℄s

Fig. 5

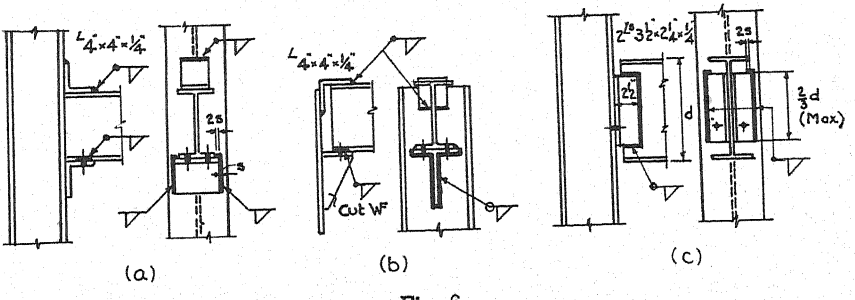

L 4"×4"×¼"
2s
s
(a)
L 4"×4"×¼"
cut WF
(b)
2 L 3½"×2½"×¼"
2s
2½"
d
⅔d (Max.)
(c)

Fig. 6

The rotation of the ends of a simple-span beam under loading produces a horizontal movement of the top of the beam, with respect to the bottom, which may be expressed as,

$$e_1 = d\phi$$

where d is the beam depth and ϕ is the slope of the elastic line at the end of the beam. If ϕ is written, substituting the equivalent internal resisting moment of the beam $\left(M = fS = \frac{2fI}{d}\right)$, for the more commonly used moment of external loads, it will be found that the extent of this movement, e_1, varies directly as the maximum bending stress at mid-span, and as the span length, but that it is not affected by the depth of the beam. Thus, in the case of uniform loading

$$e_1 = d\phi = d\left(\frac{ML}{3EI}\right) = \frac{dL}{3EI}\left(\frac{2fI}{d}\right) = \frac{fL}{3{,}625{,}000}$$

where f is the maximum unit bending stress at mid-span and L is the span length in feet. This is based on $E = 29{,}000{,}000$. For a beam, loaded to produce a 20,000 psi. bending stress at the middle of a 20-ft. span, e_1 would be 0.11 in. If the same stress were produced by a single concentrated load at the mid-point of the 20-ft. span, the displacement would be 0.083 in., or but 75% as much as under uniform loading producing the same maximum stress.

In their paper, "Tests of Miscellaneous Welded Building Connections,"* presented before the October 1941 Convention of the AMERICAN WELDING SOCIETY, Messrs. Johnston and Deits have not only contributed considerable new and valuable data on the behavior of a number of types of flexible and semi-rigid beam-to-column connections, but have suggested a method for evaluating the strength-rotation properties of any flexible or semi-rigid type connection. By plotting a "beam line" for the largest L/d ratio likely to be used in beam design, the factor of safety, in terms of strength and maximum required rotation, can be determined from the moment-rotation curve, plotted from tests, for any particular connection type.

Seats and Brackets

Welds for fastening seat angles to the supporting columns must be designed to carry the beam reaction in shear, combined with the "bending" effect of the load applied at some point on the outstanding leg, away from the column face and hence outside the plane of the welds. The actual location of this load application with reference to the face of the column is dependent upon the stiffness of the outstanding leg (relative length and thickness) and, to a certain extent, upon the stability of the beam web. For a more complete discussion of the problem the reader is referred to "The Practical Design of Welded Steel Structures" by H. M. Priest, appearing in *The Welding Journal*, August 1933; the work of Prof. Inge Lyse and associates at Lehigh University, reported in the February and June 1935, October 1936 and October 1937 issues of The *Welding Journal;* and the May 1941 progress report of A.I.S.C. Committee on Technical Research on the current program at Lehigh University investigating the effect of seat angle stiffness upon beam web stability.

* *The Welding Journal*, January 1942.

When the beam reaction is large enough to require a stiffener, the seat may be cut from an I-beam to form a T-shape bracket with the web functioning as a stiffener, or made from two plates. With stiffened seats the load is assumed to be applied at the outer edge of the seat and the moment, due to eccentric loading, provided for accordingly in the design of the welding.

Architectural requirements frequently necessitate locating the beams considerably off the center line of the columns to which they frame, and at the same time limit the space in which the connection can be made. The variety of such cases is too great to be covered by this chapter and the limited number of applications of any one solution recommends leaving the general problem to the ingenuity of the designer. The fundamental precepts, already discussed, namely, (1) that sufficient flexibility be provided to accommodate end rotation or that sufficient strength be provided to resist the stresses induced by any inherent stiffness and (2) that provision be made for the stresses in the welds caused by eccentric loading, must not be overlooked in meeting the architectural limitations.

Wind Connections

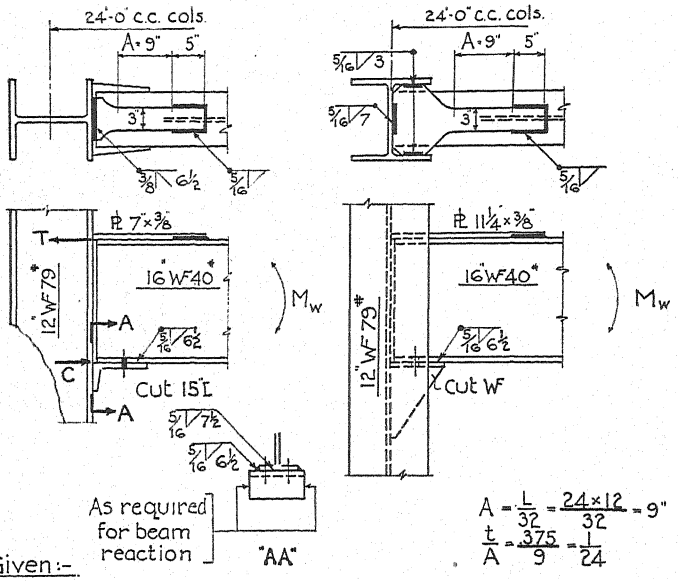
When it is required that the beam-to-column connection, in addition to supporting the reaction from the gravity loading, brace the frame to resist wind forces, the conception of flexibility to accommodate simple-span assumptions must give way regardless of what basic assumptions were employed in proportioning the framing. When the beam is small, a sufficient amount of direct welding can be employed where the top and bottom flanges join the column to develop the capacity of the beam in bending. For larger beams such practice is uneconomical.

In the latter case, a plate or bar may be welded to the top beam-flange and the column, provided that (1) the bar is of sufficient cross-sectional area to carry the wind moment couple at the allowable working stresses, (2) the welds attaching the bar to the beam and the column are adequate to resist a force in excess of that which will produce yield point stress in the bar and (3) the welds at opposite ends of the bar are sufficiently separated to permit plastic deformation in the bar resulting from combined wind and gravity moments. If this separation is of sufficient length so that the deformation caused by the gravity loading is completed at stresses only slightly above the yield point, no injury to the metal will result—the gravity load deformation being similar in character to the "cold working" frequently required in the fabrication of structural steel.

If the nature of the gravity loading were such as to cause repeated reversal of stress, this solution might be subject to question, but such is not the case in tier buildings. The wind loading must, of course, be assumed to alternate in direction, but having deformed once to accommodate the gravity stresses, the bars are of sufficient size to resist the wind loading within the permitted stresses.

Figure 7 shows two types of wind connections designed in accordance with the foregoing principle.* If the separation, A, between welds at the

* Pilot tests at Lehigh as reported in the paper, "Tests of Miscellaneous Welded Building Connections," published in *The Welding Journal* for January 1942, indicate that the design of the welding in these illustrations may be unnecessarily conservative.



Given:-

Wind moment, M_W = 40,000 ft-lbs.

$T = C = \frac{40{,}000 \times 12}{16} = 30{,}000$ lbs.

Required area of top plate for wind = $\frac{30{,}000}{20{,}000 \times 1.33} = 1.125"$, use 3"×⅜"

Amount of 5/16" fillet welds required for wind = $\frac{30{,}000}{3{,}000 \times 1.33} = 7.5"$

Approx. load required
to develop yield point stress in top plate = 33,000×1.125 = 37,000 lbs.
At permitted stress, 13" of 5/16" fillet weld will develop 3,000×13 = 39,000 lbs.
" " " 6½" - ⅜" butt " " " 6,000×6.5 = 39,000 lbs.

Fig. 7

ends of the top bar is approximately $^1/_{32}$ of the beam span, the deformation to accommodate the gravity loading may be assumed to take place at about the yield point stress in the bar. Since, under wind loading the top bar may be subject to compressive stresses, its thickness should not be less than one twenty-fifth of the separation, A.

Columns

Milled column splices in tier buildings ordinarily require only a nominal amount of welding to hold the parts joined securely in place, since the load is transferred directly through the contact surfaces and the spliced shafts are stayed laterally by the floor framing, near which the splices occur.

Figure 8 shows typical column splices used in tier buildings. Type *a* should only be used where the depths of the sections joined are so nearly the same that no fillers are required. When the nominal sizes are the same, but the actual difference too great to use type *a*, the butt plate in type *b* may be of nominal thickness, commonly $^5/_8$ in.; otherwise the thickness of

these plates must be sufficient to care for the bending resulting from the offset in the flanges above and below the splice. Column splices, remote from horizontal framing capable of affording lateral support, should be designed to provide a degree of continuity past the splice. A provision in the A.W.S. Building Code requires that such splices be proportioned for 50% of the axial column load. The Code also requires that adequate welding be provided to care for any net tension across the spliced plane, resulting from wind forces acting in conjunction with 75% of the dead loading and no live loading, provided this condition of loading produces the greatest net tension.

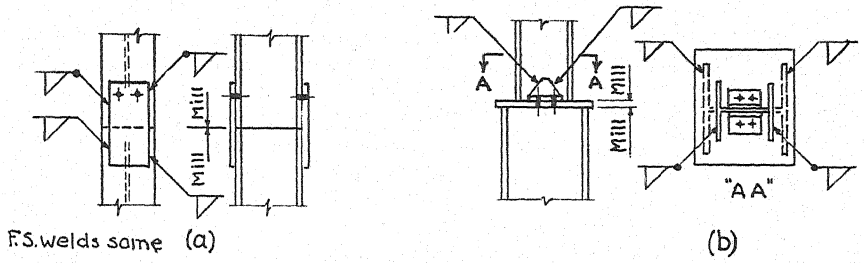


Fig. 8

The welding, if any, required at a column base plate, need only be sufficient to hold the column securely in place. On lighter columns with moderate size base plates, it is customary to attach the plates directly to the column, in the shop (see Fig. 9a). Where the plates are large enough to produce an awkward shipping piece or where the erector prefers to level up and grout the plates in place prior to commencing erection, lugs, with holes located to accommodate the anchor bolts, are shop welded to the columns and no field welding of these lugs to the base plates is required (see Fig. 9b).

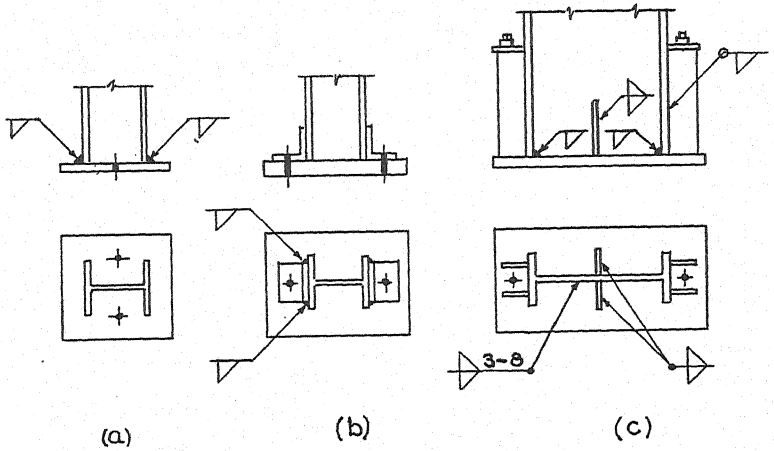


Fig. 9

If the column design is predicated upon a definite amount of horizontal shear and moment transfer to the foundation as is frequently the case in rigid frames and certain types of mill-building columns, the base detail must be designed to provide for this shear and moment without sensible distortion in the detail parts (see Fig. 9c).

Girder Design—Details and Fabrication

While the use of cover plates to increase the area of the flanges is generally not economical in the case of built-up girders because of the amount of welding involved, they are used frequently on rolled beam sections where the loading conditions (as, for example, a single heavy concentrated load at mid-span) can be satisfied with relatively short cover plates. Fillet welds, for attaching the cover plates, must be sufficient to transfer the increment of bending stress (horizontal shear) from the plates to the beam, with a maximum clear spacing between intermittent welds not exceeding 16 times the thickness of the compression flange plate, 24 times the thickness of the tension flange plate and not more than 12 in. in any case. Welding should be continuous across the ends of the cover plates and for a distance, equal to the plate width, back from the ends. The horizontal shear per linear inch between the plates and the beam, to be carried by the welds at any given point, along the plate is equal to,

$$f_w = \frac{VQ}{I}$$

where

f_w = horizontal shear per linear inch of weld.

V = total vertical shear at the point considered.

Q = the product of the area outside the shear plane (in this case the area of the cover plate to be welded to one flange of the beam) multiplied by the distance from the centroid of this area to the neutral axis of the gross cross-section of the beam or girder.

I = the gross moment of inertia of the girder at the point considered.

In built-up girders, variation in the required area of a flange, as determined by the variation in bending stress, can be most economically provided by splicing plates of different thicknesses, provided the possible saving in flange material is sufficiently large to justify the expense of the splices. Such transverse splices should be made directly with butt welds. They should be made prior to welding the flanges to the web, to avoid locked-up stresses resulting from the cooling of the splice welds. A constant flange width, with variable thickness, is preferred to variable width and constant thickness. Although earlier practice sometimes required that the splices in flange plates be made at angles other than normal to the plane of the web, there is little evidence to support it in building construction and the preference is for making the splices at right angles to the web. When splices are made at a skewed angle, the total capacity of the weld is rated the same as if it were normal to the axis of the plates.

Web splices, if required, should be butt welds for the entire width of the plate. As in the case of the flange splices, they should be made before the web-flange welds are deposited. A wandering sequence should be

followed to balance the heat input about the center line of the web. Where the shear intensity varies widely, as is the case in a girder whose principal loading consists of heavy concentrations relatively near each end, the possible saving in web plate material in the section between the loads may justify the introduction of splices not otherwise required. In this case the thicker plates should be extended into the zone of low shear somewhat beyond the theoretical point of change—say, 8 to 12 ins. Two limiting requirements must be borne in mind where a change in web thickness is contemplated to take advantage of variations in shear intensity. First, no web should be thinner than $\frac{1}{170}$ of its depth. Secondly, when the ratio of depth to thickness, h/t, equals or exceeds 70, intermediate stiffeners are required if h/t exceeds $8000/\sqrt{v}$, where v is the maximum unit shear in pounds per square inch. The spacing, d, between such intermediate stiffeners, is determined by the formula,

$$d = \frac{270{,}000t}{v} \sqrt[3]{\frac{vt}{h}}$$

with a maximum of 7 ft. 0 in.

Welds attaching the flanges to the web plate, in light girders with relatively thin web plates, are generally of the fillet type, symmetrical about a plane through the mid-thickness of the web plate. If intermittent spacing is used, the welds should be spaced identically on both sides of the web and the rules for maximum spacing already discussed in connection with cover plates should apply. When the intensity of the horizontal shear to be carried by these welds remains more or less constant for the entire length (as, for instance, where the principal loading is concentrated near the mid-span) and where the size of fillet welds required by the shear becomes so large as to be uneconomical, butt welds are to be preferred. Crane girders are likely to fall in this category since the movement of the wheel loads develops large horizontal shear stresses which are maximum for any given point when the moving load is placed at that point. The welds under the top flange, furthermore, are usually subjected to the application of a direct concentration in transferring the wheel load to the web. Similarly as with cover-plated rolled beams, the amount of horizontal shearing stress to be carried by the welds connecting the flange to the web, may be determined at any given point, by the expression,

$$f_w = \frac{VQ}{I}$$

If intermittent welds are used, spaced so that the ratio of weld length to total length is r, the nominal size, s, of each fillet may be determined by the expression,

$$s = \frac{f_w}{19{,}200r} = \frac{VQ}{19{,}200Ir}$$

(2 welds $\times$ 0.707 $\times$ 13,600 psi. = 19,200 lb. per linear inch). The web-flange welding should preferably be executed concurrently on both sides of the web and a wandering sequence employed to balance the heat input about the center lines of the girder.

Stiffeners are required at points of concentrated loads. The compressive stress in such stiffeners should be limited to 17,000 psi. In general, bars are used for stiffeners, but under columns turned with their webs normal to the girder web, T's cut from *WF* sections and located so that the flanges of the T's are directly under the column flanges, are frequently used. The welds attaching stiffeners to the girder web must be adequate to transfer the load from the stiffener to the web plate or vice versa. For intermediate stiffeners not carrying calculated stress, the maximum spacing between stitch welds should not exceed 12 in. The ends of stiffeners should be closely fitted to bear against the flange plates and the stiffeners should be wide enough to extend nearly to the edge of the flange plate. If the ends of the stiffeners are welded to the flange plates, a sufficient amount of welding must be used to carry the entire load transferred to the stiffener. Ends of stiffeners on crane girders should not be welded to the tension flange. The inside corners of stiffeners should be clipped to clear the fillets, and if the web-flange welding is continuous, the clipping should provide clearance for the manipulation of the electrode past the stiffener.

Truss Design—Details and Fabrication

Trusses may be broadly grouped into two categories. In one category might be included roof trusses and other lightly loaded trusses of short or medium spans; the other would include longer span trusses of moderate loading and trusses supporting heavy loads.

A number of ingenious designs for short spans and light loads have been developed, in which the composition, because of the ease afforded by welding in making the joints, has departed from the older conventions. Such designs, however, have usually been successful in realizing the greater part of the anticipated economies, only where a sufficient duplication has made possible the introduction of proper assembly jigs, handling equipment, organization and shop training—in short, standardization.

Where such duplication does not exist, the designer will do well to bear in mind the usual shop practice in truss assembly when selecting the member sections. At the same time he must not lose sight of the advantages peculiar to welding in the design of the joints. For moderately light trusses angles in pairs, or single angles if load requirements are small enough to preclude the use of double angles of the minimum desirable size, are generally used for the web members. The chords, however, are frequently structural tees, cut from wide flange sections, since the stem of the tees provides a space for the web member connections. These tees are obtainable at the rolling mills, sheared and straightened. Since two tee sections are formed by the splitting of a beam, the designer should arrange to use both pieces to avoid an extra charge for re-stocking the unused piece. Typical joints of trusses composed of angle web members and structural tee section chords are shown in Fig. 10.

It is currently considered good practice, in designing truss joints of angle web members, to arrange the welds so that the centroid of the weld group approximately coincides with the center of gravity of the angle or, when such an arrangement is not feasible, to require additional welding to compensate for assumed higher stresses resulting from the assumed eccen-

tricity. An arrangement of welds to coincide with the center of gravity of the web angles is shown in Fig. 10c.

In the case of moderate-sized angle web members, some fabricators will elect to weld all around the end of the angle even at the expense of having to do somewhat more welding. This is to avoid the greater expense of meticulous measurements incidental to a "balanced" design requiring a minimum of welding. When this practice is followed, control dimensions similar to those shown in Fig. 10b are given on the shop drawing to insure proper location of the member and a sufficient amount of "all-around" welding.

Recent tests on the effect of eccentricity between the weld group and angle welded, reported by Messrs. G. J. Gibson and B. T. Wake in a paper entitled, "An Investigation of Welded Connections for Angle Tension Members" in the January 1942 issue of *The Welding Journal*, indicate that for moderate-sized angles at least, the actual effect of this eccentricity is considerably less apparent than heretofore supposed and that, as a practical matter, some simplification of current practice might be justified.

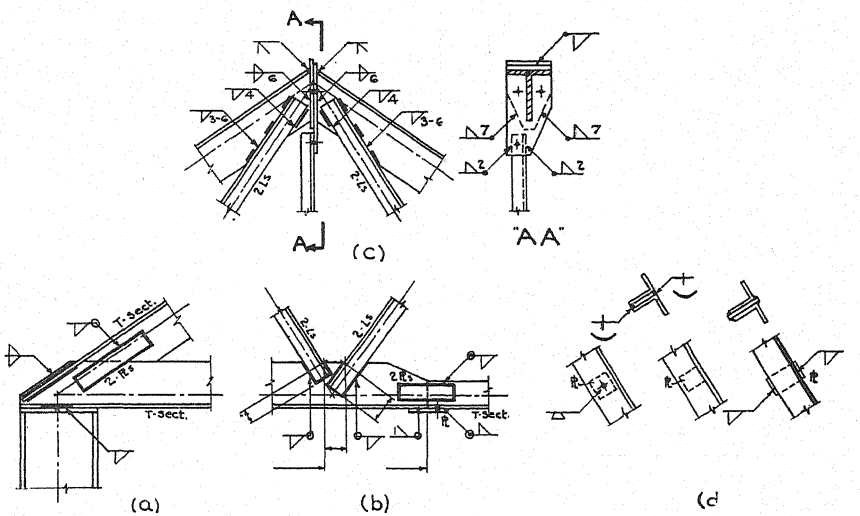


Fig. 10

Members made up of component parts, as, for example, two-angle web members, must be joined to act in unison. Not only is it imperative that each element of compression members have individual ratios of slenderness somewhat less than that for which the whole member was designed, but even tension members should be tied to insure against injury in handling prior to their installation in the building. Typical tie details are shown in Fig. 10d.

Trusses having stresses beyond the capacity of double-angle web members are generally built of rolled beam or column sections. The chords for such trusses may be (1) a single rolled section of the size determined by the maximum stress in any of the panels; (2) spliced at one or more panel points

to save weight in the lower stressed panels or (3) a rolled section core, selected on the basis of end-panel stress, with reinforcing plates added in pairs as required by the larger stresses in the interior panels. The amount and variation of stress, as well as the length and number of panels, will determine which of these methods is the most economical when the cost of the additional shop work is balanced against the possible saving of material.

The webs of rolled beam sections are usually turned normal to the plane of the truss. Gusset plates, in pairs, in contact with the flanges of the rolled sections, can be used to transfer the stress from member to member at the joints. However, where the thickness of the members is sufficient to permit, and considerable stress is to be transferred, direct butt welds will save enough in connection material and welding to more than pay for the expense of the joint preparation required for the butt welding. Figure 11

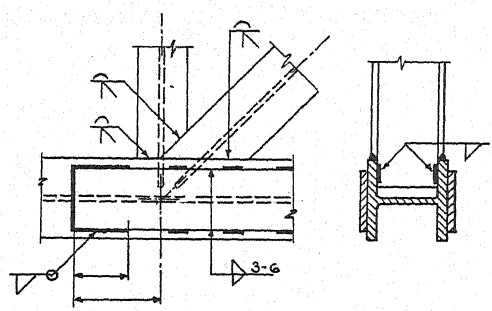


Fig. 11

shows a typical butt-welded joint.* Gusset plates should be avoided when the variation in depth of the rolled sections meeting at a point would necessitate the use of fillers to build out the shallower members. When gusset plates are employed, their size is determined by the amount and disposition of the fillet welds required by the stress in each member, after which the thickness is obtained by limiting the shearing stress on the critical section of each plate to the permissible maximum. In order to increase the perimeter for welding without a corresponding increase in the size of a gusset plate, it is frequently advantageous to provide slots around which fillet welds can be deposited. Plug welds and slot welds completely inside the perimeter can also be employed to assist in carrying stress. When this is done the resulting net section must be investigated, as the full value of the welding cannot be counted upon unless the stress in the net section of the base metal falls below the permissible limit.

Welds must be located so as to be easily accessible for the manipulation of the electrode. When butt welds are employed, the sequence of welding should be such that the shrinkage, due to cooling, takes place as far as possible before the closure joints producing a locked-up frame, are made. In the welding of locked-up frames the joints completed last should occur in members subject to compression under service loading.

* A number of truss joints designed to eliminate the use of gusset plates by the proper selection of main member material are shown in a paper, "The Practical Design of Welded Steel Structures," by H. M. Priest published in *The Welding Journal*, August 1933, and in "Design of Welded Trusses" by A. Vogel, published by the General Electric Co., Schenectady, N. Y.

If, due to otherwise excessive handling weight or dimensions, field splices are required, they may be made by direct butt welds, fillet-welded butt straps, or a combination of butt welds and fillet-welded straps. A function of the straps is to assist in the field assembly of the splice. Investigations point to their having a somewhat lower efficiency under fatigue loading, but this fatigue condition seldom enters into building construction. Compression members may be milled at the field splice but even when the stress is transferred directly across the milled contact surfaces, sufficient welding is required to hold the spliced parts securely in alignment. Butt straps must not be welded on both sides of the splice until the milled surfaces are in good contact throughout their entire area.

Tolerances

In the rolling of structural shapes, some variation from the theoretical handbook dimensions is inevitable. While this fact is well known to fabricators it is sometimes overlooked by the designer. This oversight may lead to otherwise avoidable fabricating costs resulting from the execution of design features which make no allowance for "mill tolerances."

The permitted variations from theoretical dimensions, or mill tolerances, are established by mutual agreement between the producers and users of structural shapes and plates, and may be found in any rolling mill handbook and the A.I.S.C. Manual of Steel Construction. Welded connections should be so designed as to anticipate variations up to the maximum permitted tolerance or a method for their compensation should be decided upon in advance. In many cases it is not feasible to match separate shipping pieces in the shop, so that the first knowledge of any variation is gained only after the parts are brought together during the field erection, when, for lack of the proper facilities, little, if anything, can be done to correct the variance. In this connection it should be noted that these variations are more apt to prove cumulative, when several parts are involved, than they are to cancel one another.

Erection and Field Welding

While clamps and clamping devices are used extensively in the shop to hold parts to be welded, they are not in general use in field erection, except possibly where parts are assembled and welded on the ground before being raised into final position. Ordinarily rough bolts in punched holes are used to secure the erected parts prior to field welding. Preference is usually given to the practice of locating holes for field bolting in detail parts which are welded to the main member in the shop. This is to avoid the expense of handling the larger part for punching or drilling. However, it is the practice with many fabricators to make occasional holes with a torch, in members too heavy for easy handling. The avoidance of holes in the main member, therefore, should not be carried to the point where awkward details and excessive welding result.

It has been found to be a practical necessity to provide a minimum of two holes in each field connection. By inserting the pointed handle of a spud wrench in one hole, the erector can apply a prying force to line up the work and hold it while inserting a bolt in the other hole. More than the mini-

mum two holes may be required for bolts to hold the parts in close contact if the welding is widely dispersed. A sufficient number of bolts, of course, must be provided to carry all of the erection loads that may be applied prior to welding, including forces resulting from the operation of the erecting derrick and its guys.

Many fabricators omit field welding, and use only bolted connections for light beams, roof purlins, bracing and, when the building code provisions will permit, on all connections of secondary beams. It has not been found to be profitable to remove erection bolts for their salvage value.

Field splices in rigid frames can frequently be made most economically while the parts are assembled on blocking on the ground, and the bent erected subsequently as a single unit. Since the scheme for erecting such framing would have some bearing upon the design of the splice connection, it should, if possible, be decided in advance.

At least as much of the framing as would be affected by the stiffness resulting from the field welding must be plumbed and secured with temporary guys or bracing in advance of the welding operators. The operators can follow along behind the raising gang at least as closely as could riveters on riveted work. In fact, they can often work even closer to them, their progress being limited only by the plumbing of the erected framework.

Because of dimensional variations resulting from mill tolerances, and due to other factors beyond the control of even the most careful fabrication, closures for field-welded butt joints are not always as perfect as planned. When such conditions arise, the root opening must not be less than prescribed. Larger openings are not detrimental to sound work when properly handled. Minimum root openings are prescribed to insure complete penetration for a sound root pass. It is not likely that a fabricator will elect to exceed the minimum opening any more than he can help, for even a slight increase in the spacing of the parts increases substantially the amount of weld metal to be deposited and hence the total cost of the work. When moderate increases occur it is customary to correct the groove by building out one or both edges to the intended outline and permitting the work to cool before depositing the root pass. If the total amount of weld metal to be deposited, as a result of imperfect closure, greatly exceeds that required for two joints of the size specified, a sufficient amount of the base metal may be cut away to permit insertion of a coupon of equal cross-sectional area and sufficient length to produce grooves at each end having normal dimensions, separated enough to avoid high concentration of heat. The welding in one of these joints should then be completed and permitted to cool before the second is started.

Unlike riveted connections, where the open holes show unmistakably the work to be done, field-welded construction requires that the field forces and the inspector be given detailed instruction as to the size, type, location and sometimes the sequence of the required welds. Under ideal conditions of duplication on straight beam-to-beam and beam-to-column framing involving no special connections, these instructions may be provided by notes or typical sketches on the erection plans. Otherwise complete details of the welding must be shown on a sketch. It has been found convenient to present these sketches on forms small enough to be slipped into a workman's pocket, identifying each connection, in the sequence in which it

is given on the sketches, with a number that appears on the erection plan opposite the point at which the joint occurs in the framing.

Inspection

By the nature of the work, inspection of the welds used in building construction is entirely visual and consists of gaging for dimension and surface contour, examination for undercutting, overlap, slag inclusion and incipient cracks, together with intermittent observation of the welding practise of each operator through a shield, to determine that each operator maintains a clean pool and gets good penetration at the root. Only operators who have met the requirements of an applicable qualification test, such as that which is provided in the A.W.S. Building Code, should be permitted to weld, either in the field or in the shop.

Much has been written of the duties devolving upon the welding inspector. Little discussed, but of very real importance, is the requirement that he make certain that *all* of the welds called for are made. He may elect to measure and mark on the steel the size and limits of the specified welds in advance of the operator, after which it is a simple matter to check the performance against his marks. Generally it is found to be desirable that the work be laid out in advance of the welding so that the operator is then free to concentrate on the welding only. However it is arranged, it is important that a systematic method be followed to insure that none of the specified welds is omitted.

CHAPTER 36B

BRIDGES*

Specifications, Materials, Design, Economies and Application, Joints, Tests and Inspection.

A—SPECIFICATIONS

A.W.S. Bridge Specifications

IN 1934 the AMERICAN WELDING SOCIETY, responding to a necessity already evident, appointed a committee "To Prepare a Specification for the Design, Construction, Alteration and Repair of Highway and Railroad Bridges by Fusion Welding." The personnel of this Committee comprised men whose activities had been associated with welding in all of its diversified branches, and others who were specialists in the design and construction of highway and railway bridges. The personnel of this Committee was extensively represented in the membership of various national engineering societies, and its Chairman, the late P. G. Lang, Jr., was the Engineer of Bridges of the Baltimore and Ohio Railroad.

After a long period of study of experience in welded bridge construction as carried out in foreign countries as well as experience in the United States, and after digesting all the available results of research in welding, the Committee prepared a specification which was published by the Society in 1936, and recommended for the practical test of actual use.

Coverage

The A.W.S. Specification for Bridges comprises sections and coverage as follows:

Section 1—General Provisions—sets forth that this is not a complete bridge specification but only for the matters affected by the fact of its being a welded bridge; expresses the authority for welding and restricts the specification to certain materials.

Section 2—Design of New Bridges—gives working stresses for weld metal, and for the parent metal when the adoption of welding or the form of joint necessitates a change therein; names the permissible and prohibited types of joints; shows approved forms for joints, gives approved ranges of dimensions for joints, such as angle of groove opening, root spac-

* Prepared by committee consisting of Jonathan Jones, Bethlehem Steel Co., *Chairman;* F. H. Frankland, American Institute of Steel Construction; LaMotte Grover, Air Reduction Sales Co.; L. S. Moisseiff, Consulting Engineer; A. R. Wilson, Pennsylvania R.R.

ing, etc.; specifies or advises regarding arrangement of parts wherever the differences between welded and alternative constructions make this advisable.

Section 3—Strengthening and Repairing of Existing Bridges—covers materials, design and workmanship in that field.

Section 4—Filler Metal—stipulates the several Classification Numbers in the A.S.T.M.-A.W.S. Specification for Filler Metal A233 which may be employed in bridge construction.

Section—Equipment and Processes—autho rizes arc and gas welding on equal terms, and calls for the use of equipment and devices affording adequate control.

Section 6—Workmanship and Technique—specifies preparation of material, assembly, establishment of sequence and control, current limitation, flame characteristics, weld layer and bead dimensions, technique for making filled plug welds, quality of weld metal, corrections, cleaning, etc., etc.

Section 7—Inspection—gives detailed instructions for making and recording the inspection of filler metal, of qualification tests and of the projected welding; this latter is emphasized because of the Committee's feeling that only under the closest inspection and control can the welding of bridges be sanctioned.

Section 8—Qualification—makes, first of all, the provision that if the joint forms, the material and the technique conform to those required by the preceding Sections, the procedure is approved without qualification tests; then, for all other cases, provides full details of procedure qualification patterned after the Standard Qualification Procedure of the Society; calls for qualification tests for all operators, and provides full details for those tests and stipulations as to their recording and renewal.

Appendices, which are not mandatory parts of the Specification, explain the origin of the unit stress allowances and cover definitions and symbols adequately for bridge construction. A Foreword, also not mandatory, gives some advice to designers, and some explanation of the Committee's attitude toward the responsibilities of those concerned with bridge welding.

Acceptance and Use

After the first edition of the Society's Bridge Specification was published in 1936, the original Committee was discharged, and the Society created a "Permanent Committee for the Interpretation and Review of the Bridge Welding Specifications of the Society." The American Railway Engineering Association and the American Association of State Highway Officials appointed representatives on this Committee, and in November, 1936, it became officially known as "The Conference Committee for Specifications for Welding of Bridges, of the AMERICAN WELDING SOCIETY." Later in the same year consideration was given to official adoption of the American Welding Society Bridge Specifications by the American Railway Engineering Association and the American Association of State Highway Officials.

The action taken by A.R.E.A. was that the Specifications adopted by the AMERICAN WELDING SOCIETY in 1936 should be used pending further consideration of the subject by the A.R.E.A. Bridge Committee. That action has not yet been modified.

The action of A.A.S.H.O., as confirmed by the provisions of its revised (1941) "Standard Specifications for Highway Bridges," is that welding of steel structures, when authorized, shall conform to the A.W.S. Specification for Welded Highway and Railway Bridges.

The Conference Committee reviewed the Specification in 1938 and issued a second edition, in which a number of the articles were re-studied and improved. In 1940, however, it undertook a complete review and in 1941 issued a third edition.

Perhaps the longest step forward, taken in this re-writing, has been the setting up of a rather complete series of joint forms which, when welded with prescribed technique, are considered to be the Standards of the Bridge Committee, and are permissible on welded bridges without any tests for qualification of procedure.

While the welding of entire bridges is not proceeding rapidly in this country, the welding of parts of bridges is; and it is now very common to find bridge specifications requiring that all such welded parts shall conform to the Society's Specification. No other specification for welding has any nation-wide standing in the bridge field, in the United States.

B—MATERIALS

The A.W.S. Specification for Bridges stipulates for new structures the use of a special specification for base material. The carbon and manganese contents are limited to 0.25% and 0.70% respectively, to ensure weldability. The physical test requirements are, on thin material, those of the A.S.T.M. Standard Specifications A7; but as thicknesses increase, the minimum acceptable tensile strengths are moderately reduced to accommodate an unescapable metallurgical fact.

The specified electrodes are those in the E-60 classification in the 1940 A.S.T.M.-A.W.S. Joint Specification for Filler Metal.

The use in welded bridge construction of high-tensile steels such as "structural silicon," "structural nickel," and other steels of higher strength than that called for in A.S.T.M. A7 Specifications, is not covered by the A.W.S. Specification for Bridges.

The inability to stress-relieve welded connections for bridges, for reasons of practical shop fabrication and field erection economies, has thus far precluded the writing of A.W.S. Specifications for the use of any but carbon structural steel of the grade above defined. An exception is the use of wrought iron welded to wrought iron, in the repair or strengthening of an existing structure, or the use of wrought iron for corrosion-resistant purposes. In the first instance working stresses lower than for carbon structural steel are used, and in the second instance the wrought iron is not used as a stress-carrying material. Where wrought-iron base metal is to be used in the repair or strengthening of an existing bridge of this metal, or where it is used for special corrosion-resisting purposes, such as for blast and cover plates, the material answers the requirements of A.S.T.M. Specifications A207 for bars and shapes, and A42 for plates.

The physical characteristics and the limiting chemical characteristics of the proposed steel for new bridges are as follows:

In addition to conforming to the requirements as to chemical composition prescribed in Specification A7, the steel shall have a carbon content not exceeding 0.25 per cent and a manganese content not exceeding 0.70 per cent, by ladle analysis. The material shall conform to the following requirements as to tensile strength and yield point:

	Thickness* or Diameter, in Inches			
	Sections, Not Over 5/8. Plates and Bars Not Over 3/4	Sections, Over 5/8 to 1 1/4 Incl. Plates and Bars, Over 3/4 to 1 1/4 Incl.	Plates, Sections and Bars Over 1 1/4 to 2 Incl.	Plates, Sections and Bars, Over 2 to 2 1/2 Incl.
Tensile Strength, psi.	60,000 to 72,000	58,000 to 70,000	56,000 to 68,000	54,000 to 66,000
Yield Point, min., psi.	0.5 tens. str.	0.5 tens. str.	0.5 tens. str.	0.5 tens. str.
but in no case less than	33,000	32,000	31,000	30,000

* The thickness of a section shall, in applying the tensile requirements of this table, be taken as the rolled thickness of the portion from which the tensile specimen is taken.

The physical characteristics of the aforementioned wrought iron are, for A.S.T.M. A207 Specifications:

Tensile Requirements

	Round, Square and Hexagonal Bars		
	Under 1 5/8 In. in Diameter or Thickness	1 5/8 In. and Up to but Not Including 2 1/2 In. in Diameter or Thickness	2 1/2 In. and Over in Diameter or Thickness; All Flat Bars and Shapes
Tensile strength, min., psi.	48,000	47,000	46,000*†
Yield point, min., psi.	0.60 TS.	0.55 TS.	0.50 TS.
Elong. in 8 in., min., %	25	22	20
Reduction of area, min., %	40	35	30‡

* When the cross-sectional area exceeds 12 sq. in., the allowable minimum tensile strength shall be 45,000 psi.

† For sections less than 3/16 in. in thickness, no tension tests will be required.

‡ For flat bars, shapes and sections less than 3/8 in. in thickness, no reduction of area test will be required.

and for A.S.T.M. A42 Specifications:

Tensile Properties

Standard Plate.—Standard plate shall conform to the following requirements as to tensile properties. These requirements apply only to longitudinal test specimens; no transverse tests shall be made.

Tensile strength, min., psi.	48,000
Yield point, min., psi.	27,000
Elongation in 8 in., min., %	14

Chemical Composition

The iron shall conform to the following requirement as to chemical composition:

Manganese, max., %	0.06

The several electrode Classification Numbers admitted for use by the A.W.S. Bridge Specification, are differentiated as follows:

Specifications for Arc-Welding Electrodes A.W.S.-A.S.T.M. (A 233)
Table I—Tensile Requirements of Deposited Metal

Electrode Classification Number	Capable of Producing Satisfactory Welds in Positions Shown*	General Description	Tensile Requirements of Material Deposited from 5/32-, 3/16- and 7/32-In. Electrodes (Not Stress Relieved)	
			Tensile Strength, Min., Psi.	Elongation in 2 In., Min., %
E6010	F, V, OH, H	Heavy covering, useful with d.c., electrode positive only	65,000	22
E6011	F, V, OH, H	Heavy covering useful with d.c., either polarity or with a.c.	65,000	22
E6012	F, V, OH, H	Heavy covering, usually used with electrode negative, d.c. or on a.c.	65,000	17
E6013	F, V, OH, H	Heavy covering, usually used on a.c.	65,000	17
E6020	H-Fillets, F	Heavy covering, usually used with electrode negative or a.c. for fillets, and electrode positive or a.c. for flat welding	65,000	25
E6030	F	Heavy covering, usually used with electrode positive on d.c. or with a.c.	65,000	25

* See Chapter 27 for explanation of symbols.

The tensile strength of the deposited metal from 1/8-in. electrodes shall be 105% of that prescribed in Table 1, and that from 1/4-in. and larger electrodes shall be 95% of the tensile strength prescribed in Table 1.

The elongation of the deposited metal from 1/8-in. electrodes shall be 90% of that prescribed in Table 1, and that from 1/4-in. and larger electrodes shall be 110% of the elongation prescribed in Table 1.

The use of the entire E60 series of electrode classifications is permitted; however, the comparatively low ductility of 17% for E6012 and E6013 should be noted. Under the most exacting conditions the use of E6010, E6020 and E6030 electrodes, with their higher ductility requirements, is recommended.

The selection of an electrode for the fusion welding of wrought iron is important, and it is advisable to use a coated, low carbon electrode yielding a high ductility deposit comparable to the ductility of wrought iron, and which will operate in a satisfactory manner with somewhat lower heat input than that used in welding mild steel.

Although the A.W.S. Bridge Specification covers the use only of carbon structural steel, there is an increasing demand for the use of high-strength, low alloy structural steel for use in bridge work. A standard specification

(A.S.T.M. A242–41 T) for such a grade has been agreed upon, wherein the chemical limitations are conducive to a weldable grade of metal.

Silicon structural steel (A.S.T.M. A94) is not recommended for welded bridges, because carbon frequently exceeds 0.35% and is admissible up to 0.40%.

High-strength, low alloy steels may be welded with low carbon electrodes, such as the E60 series, with equally satisfactory economy, in most cases, and with less likelihood of welding difficulties than when alloy electrodes of higher strength are used. Slightly longer fillet welds, made with low carbon electrodes, will develop as much strength in a connection as required with high-strength, low alloy base metal. The unit working stresses, as prescribed in the A.W.S. Bridge Specification, are based upon the use of low carbon electrodes and are the limiting factor in design.

C—DESIGN

Loads and Forces

The A.W.S. Bridge Specification contemplates that the loads and forces, the unit stresses on base material, the general requirements as to arrangement of parts, clearances, camber, etc., will be found in an applicable standard specification, such as that of A.R.E.A. for railway bridges and that of A.A.S.H.O. for highway bridges; the only exceptions being those matters which are affected by the choice of welding as the method of construction.

Fatigue Considerations

Foremost among these considerations is the effect of pulsating and reversing loads upon the connections, and, in the case of fillet-welded joints, upon the base material at the connections—an effect which is summed up in the expression "failure by fatigue." Specifications for riveted bridges have always contained a provision against this type of failure, in the form of reduced unit stresses for members subject to reversal. The requirements in the case of welded joints are not necessarily the same. Our present knowledge of them comes principally from fatigue tests of structural joints by the German State Railways at Stuttgart and from more recent tests by Committee F, Welding Research Committee, at the University of Illinois, which latter work will continue for several more years.

Fatigue failure may occur at low unit stresses under millions of repetitions of the stress cycle, or at higher and higher unit stresses under smaller and smaller numbers of repetitions, the limit being, of course, a failure under a single cycle, or application, this being the familiar static test to destruction. Therefore, the application of fatigue considerations to bridge design requires that someone exercise judgment as to the number of cycles of severe stress to be endured; otherwise, the enforcement of low unit stresses based on fatigue may become very wasteful.

The Bridge Committee's attitude, as implied in the unit stress clauses of the 1941 Specification, may be summed up as follows:

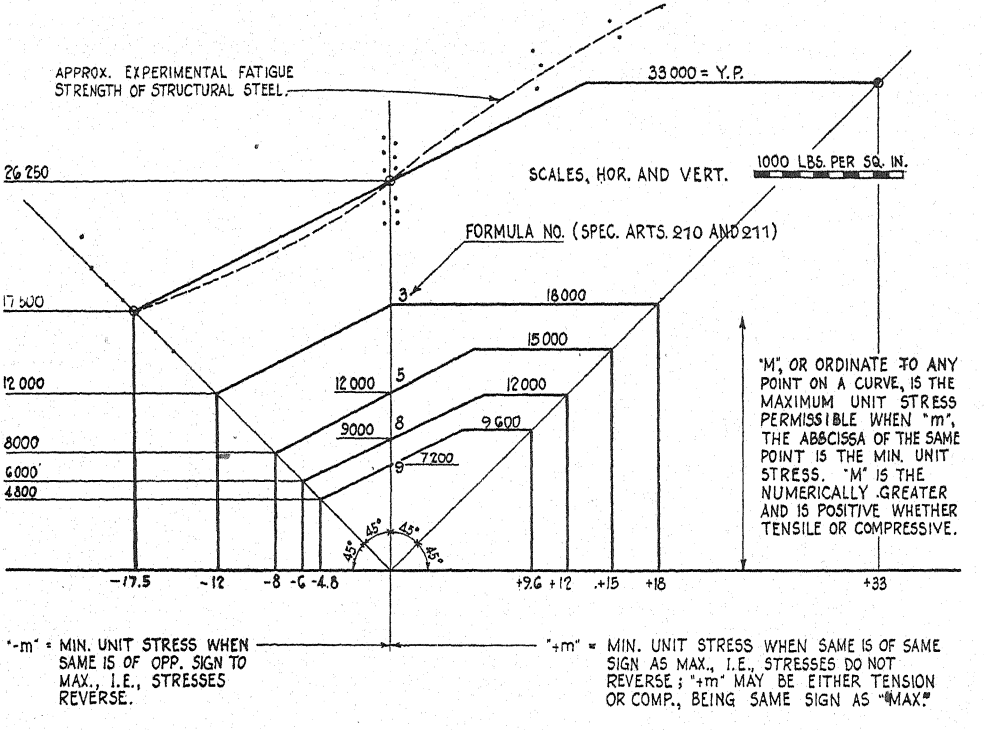
1. For railway bridges, all members and joints should be protected against two million alternations between the least, and the greatest, stress possible under the prescribed loading.

2. For highway bridges, all floor members and other parts which receive maximum stress from 60 lineal ft. or less of live loading, should be protected against the same two million alternations.

3. For the remaining members of highway bridges, the number of times that the maximum computed stress will be endured is so small that such members may be designed without regard to fatigue, i.e., at usual unit stresses for static loading.

Fatigue Data

When fatigue is to govern the design, the critical factor is the range between the maximum and the minimum computed stress, and the effect of this range must be expressed in the choice of unit stresses. Specialists in the fatigue of metals have devised a number of charts or curve forms for embracing all of the complex phenomena which they have encountered; all of those are too complex or subtle to be of use to a practicing structural engineer. All of the facts that affect bridge design are most simply expressed as in Fig. A-1.



$$m = \frac{\text{Min.}}{A}, \quad M = \frac{\text{Max.}}{A}$$

Fig. A-1

Articles referred to in Fig. A-1 and Tables 1 and 2 are in the A.W.S. Specifications for Welded Highway and Railway Bridges.

The construction of this figure is explained in full detail in Appendix A of the A.W.S. Bridge Specifications, or may be perceived from the notes it carries. The lines marked 3, 5, 8, 9 are graphs of the A.W.S. unit stress formulas of the same number, given in the tables below. The simple relationship between the plotting of the test data and the derivation of working formulas is also explained in the Appendix mentioned, and examples are there given of the facility with which the formulas can be applied to any case of bridge member or joint design.

Unit Stresses

The A.W.S. Bridge Specifications carry the following two tables for unit stress in base material and in weld metal:

TABLE 1—BASE MATERIAL

Formula No.	Type of Member	Type of Stress	Required Area, A (see Note 1)
1	Beams and Girders	Bending (with reversal)	$\frac{I}{C} = \frac{\text{Max. (Mom.)} - 1/2\ \text{Min. (Mom.)}}{18{,}000}$ (Note 2)
2	Beams and Girders	Shear (with reversal)	$A = \frac{\text{Max.} - 1/2\ \text{Min.}}{11{,}000}$
3	Axially Stressed, not connected by Fillet Welding	Tension (Max.) with reversal to Compression (Min.)	$A = \frac{\text{Max.} - 1/2\ \text{Min.}}{18{,}000}$ but not less than $\frac{\text{Min.} + 1/2\ \text{Min.}}{p}$ (Note 3)
4	Axially Stressed, not connected by Fillet Welding	Compression (Max.) with reversal to Tension (Min.)	$A = \frac{\text{Max.} - 1/2\ \text{Min.}}{p}$ (Note 3)
5	Axially Stressed, connected by Fillet Welding	Tension (Max.) Either sign for Min.	$A = \frac{\text{Max.} - 1/2\ \text{Min.}}{12{,}000}$ but not less than $\frac{\text{Max.}}{15{,}000}$ and not less than $\frac{\text{Min.} + 1/2\ \text{Min.}}{p}$
6	Axially Stressed, connected by Fillet Welding	Compression (Max.) Either sign for Min.	$A = \frac{\text{Max.} - 1/2\ \text{Min.}}{12{,}000}$ but not less than $\frac{\text{Max.} - 1/2\ \text{Min}}{p}$ and not less than $\frac{\text{Max.}}{p}$

Note 1: The values herein stated assume 18,000 lb. per sq. in. to be the basic allowable tension under the applicable general specifications. Otherwise all denominators to be modified proportionately, except that those of Formulas 5 and 6 are not to be increased.

Note 2: The denominator 18,000 is to be reduced, for the compression flange, as directed in the applicable general specifications. Thus for A. A. S. H. O. Hwy. Br. Spec. 1941, and for A. R. E. A. Rwy. Br. Spec. 1938, use $18{,}000 - 5(l/b)^2$.

Note 3: "p" = allowable compressive unit stress from the applicable general specifications. Thus for A. A. S. H. O. Hwy. Br. Spec. 1941, and for A. R. E. A. Rwy. Br. Spec. 1938, $p = 15{,}000 - {}^1/_4\,(l/r)^2$.

TABLE 2—WELD AREAS

Formula No.	Type of Weld	Type of Stress	Required Effective Weld Area, A (see Note 1)
7	Butt	Tension or Compression	$A = \dfrac{\text{Max.} - {}^1/_2\,\text{Min.}}{13{,}500}$ but not less than $\dfrac{\text{Max.}}{16{,}000}$
See Art. 212 (*c*) A. W. S. Bridge Specs. for penalty in case of single-vee backed-up welds.			
8	Butt	Shear	$A = \dfrac{\text{Max.} - {}^1/_2\,\text{Min.}}{9{,}000}$ but not less than $\dfrac{\text{Max.}}{12{,}000}$
See Art. 212 (*c*) for penalty in case of single-vee backed-up welds.			
9	Fillet	Tension, Compression or Shear	$A = \dfrac{\text{Max.} - {}^1/_2\,\text{Min.}}{7{,}200}$ but not less than $\dfrac{\text{Max.}}{9{,}600}$

NOTE 1: See Article 212 (*b*) A. W. S. Bridge Specs. for allowable stresses in butt welds made smooth and flush.

It will be found that all of the above formulas give, in the case of loading which never greatly fluctuates, the same unit stress allowance as would be expected under static conditions. Also, as above explained, a note in the specification exempts many highway bridge members from any but the static units.

The use of these formulas has at first seemed to many bridge designers, as do many innovations, rather complicated; but after trial with actual stress-sheet cases they have been quick to find and report that the application is simple. It is the Committee's belief that they are simpler than any adequate methods in use abroad or proposed as alternatives here.

Continuity and Fixity

It is very important to realize that types of construction and forms of details for properly designed welded structures are likely to be radically different from corresponding features in riveted or bolted structures or cast details, out of consideration for technical propriety as well as economy.

The inherent rigidity of direct-welded connections and their ability to develop maximum rigidity with a minimum amount of connecting material furnish a special incentive to take fullest advantage of the economy afforded by the use of rigid frames and arches, and by the use of continuous beams, girders, stringers and trusses. Members that would be designed customarily as free-ended in riveted construction are often designed more appropriately with rigid end connections when welding is used.

Where continuous construction is not feasible and simply supported beams are used, provisions must be made in the end connections so that the material can bend or deform slightly, or the supports can rotate in some way, to permit the ends of a beam to rotate as the member deflects under load. Otherwise high negative bending moments will be developed that the connections are not designed to withstand.

Such flexible or semi-flexible connections for bridge members must be designed so that after the initial deformation or adjustment has taken place under load, the range in subsequent stress under service conditions will not be such as to produce fatigue failure.

Important Details of Design

In detailing members that are subjected to severe impact or fatigue loading, it is especially important to avoid abrupt surface irregularities that may constitute "notch effects" and cause abrupt disturbances in stress paths and accompanying concentrations of high local stress. Although internal defects and discontinuities are less serious than surface defects, they also affect fatigue strength much more than they do static strength.

For further recommendations regarding the design of welded bridges the reader is referred to the A.W.S. Bridge Specifications.

D—ECONOMIES AND APPLICATION

It is in the strengthening and repair of existing bridges, and in the fabrication of auxiliary details for new bridges, that welding has found its most extensive application to bridge work in America. This is rather a different situation from that in Europe and Australia, where new welded bridge construction has been carried forward extensively along with the use of welding for repairs and alterations.

Application to Repairs

The following are some of the types of repairs and methods of strengthening for which welding is used: replacing or patching corrosion-wasted parts; building up corroded rivet heads; relieving over-stressed rivets by welding the connected parts, such as connection angles to web plates, girder flange angles to web plates, etc.; adding cover plates to girders or columns; taking up pin wear in truss bridges; adding stiffener bars to plate girders, particularly at points of concentrated bearing, and replacing corroded or damaged parts of flange angles, web plates, etc., of girders, floor beams, stringers and truss members; providing water-tight joints.

Specifications for Repair

Requirements of the A.W.S. Specification include among other details:

(*a*) Before designing any repairs to existing structures a thorough examination should be made to determine:

1. The character of the base metal in the old structure.
2. The condition of the component parts and their connections.
3. Whether the necessity for repairs is due to corrosion, failure of details due to increased live load, or insufficient original design.
4. The extent to which welding can be applied in making repairs; and whether repairs shall consist of restoring corroded parts only or of adding additional section to increase their strength.

(*b*) In the design of strengthening beyond the restoration of damaged or corroded members, a complete study of the stresses in the structure shall be made, and all parts and joints repaired or strengthened shall be made sufficient to carry the stresses in accordance with the Specification.

(*c*) Base metal shall be removed only where the member being cut is not under stress, or where such cutting is limited so that the stress in the member under existing loads after cutting shall not be greater than 50% of the maximum allowable working stress.

(*d*) No operation of actual welding or flame cutting shall be performed while moving loads are upon the structure subjecting it to shock and vibration.

(*e*) If material is added to a member carrying substantial dead load stress, either for repairing corroded parts or for strengthening, it is desirable to relieve the member of dead load stress, or to prestress the material to be added. If neither is practicable the new material to be added shall be proportioned for a unit stress equal to the allowable unit stress in the original member minus the dead load unit stress in the original member.

(*f*) Where rivets or bolts are overstressed, they shall be considered to carry the entire dead load, provided they are capable of carrying it without overstress, and welding shall be added to carry all live and impact stress. If the rivets or bolts are overstressed by dead load only, then sufficient welding shall be added to the joint to carry all of the stress (dead, live and impact).

(*g*) In strengthening members by the addition of material, it is desirable to arrange the sequence of the welding at all times so as to maintain a symmetrical section. This is of particular importance if live load is permitted upon the bridge while the member under consideration is being strengthened or repaired. In certain classes of repairs and strengthening it is important that the program of welding steps be so arranged as to preclude, so far as possible, locked-in stresses due to weld shrinkage.

New Bridges

Although two of the first all-welded bridges in the world were constructed in the United States, a great deal more new, welded bridge construction has now been carried out in Europe and Australia, where virtually all highway bridges, and most railway bridges of plate girder type, have been welded for some years.

More than 150 welded plate girder railway bridges including spans of more than 175 ft. and 500 welded highway bridges including spans up to 240 ft. have been constructed in Germany alone, the highway structures involving about 300 girder bridges and some 200 other types including truss bridges.

In Belgium, England, Sweden, Poland and other foreign countries, many welded highway bridges and a number of welded railway bridges have been built. In France there has been constructed recently a Warren-type low-truss, main line railway bridge of unique design, in which all truss member connections are butt welded.

In the United States, welded details have become standard practice with many railways and state highway bridge departments for auxiliary details and features such as cover plates for beams and girders, plate-girder stiffeners, web splices, cross-bracing and diaphragms, continuous stringer splices, filler plates, stay plates and lacing, cantilever side-walk brackets, floor expansion devices, rockers, shoes, pedestals and bolsters for supports, light weight steel and composite floors, railings, drains, electric lighting standards, splices in steel piling, caps and bracing for steel-pile bents and trestles, and foundation caissons.

A few new all-welded railway bridges have been constructed; also many highway bridges have been all-welded by state highway departments, counties and smaller municipalities, many of which have not been reported in technical magazines. Also a large number of welded bridge alteration, widening and strengthening projects have been carried out, which have involved new all-welded main members or highly responsible welds in existing or spliced members.

Examples of Welded Bridges

In Table 3 are tabulated those examples of new welded bridge construction in the United States and Canada which are most outstanding because of size, design features or comparatively early date of construction.

Rigid Frames

The following welded highway grade-separation structures constructed recently by the State Highway Department of Connecticut, on the Merritt Parkway and the Wilbur Cross Parkway between New York and Hartford and on the Hartford By-Pass, are all of rigid frame design except Jordan Lane (cantilever).

Town	Location	Span	Width
Trumbull	Trumbull Ave.	61 ft.	85.5 ft.
Greenwich	Lake Ave.	2 @ 55 ft.	30 ft.
Stratford	Route No. 8	62 ft.	64 ft.
Orange	Derby-Milford Rd.	2 @ 68 ft.	30 ft.
East Hartford	Main Street	84 ft.	34 ft.
Wethersfield	Jordan Lane	80–170–80 ft.	80 ft.

Welded Bridge Parts

Among the thousands of examples of bridge parts which have been

Table 3—Examples of Welded Bridge Construction in United States and Canada

Year of Construction	Location	Kind of Service	Type	Span Length	Width	Tons of Steel
1926	Havre de Grace, Md.	Highway	Addl. upper deck on old truss bridge	13 spans 168 ft. to 310 ft.	12-ft. roadway	...
1927–28	Chicopee Falls, Mass.	Railway	Skewed through truss	1 @ 135	Single track	80
1928	E. Pittsburgh, Pa.	Railway	Plate girder	1 @ 55	Single track	20
1930	E. Liverpool, Ohio	Highway	Stiffening trusses for suspension bridge	.....	.....	...
1932	Merced, Calif.	Highway	Steel beam	31 @ 40 7 @ 20	.....	...
1933	Chester County, Pa.	Highway	Truss	Seven short span bridges	.....	...
1933–34	Raquette River near Messena, N. Y.	Highway	Through truss	2 @ 150	20	150
1934	Wayne County, Ohio	Highway	Beam	Salvaged short beams butt welded together to make new longer spans		
	Shepards Bridge, Franklin Co., N. Y.	Highway	Plate girder	2 @ 71	.....	...
1935	Riverside and Delanco, N. J.	Highway	Truss swing bridge	2 @ 112 1 @ 160	40	470
	Florida East Coast R.R., Jupiter, Fla.	Railway	Bascule girder	50 ft. span, 70 ft. girders	Double track	...
1936	Ste. Anne de la Parade, Que.	Highway	Continuous girder	6 spans total 650 ft.	34	318
	Sullivan County, Livingston Manor, N. Y.	Highway	Through plate girder	1 @ 72	Two lanes	14 tons in main girders
1937	St. Lucie River, Stuart, Fla. Florida East Coast R.R.	Railway	Cont. beams on H-pile bents	1200 ft. total length	Double track	...
1938	Overseas Bridge, Key West, Fla.	Highway	Alteration of railway bridge to 24-ft. highway bridge	250 ft.	Swing span	...
1939	Treasure Island Bridge, St. Petersburg, Fla.	Highway	Two leaf bascule girder span	.....	.....	...
	Bay 8th St. Bridge, Shore Parkway, Brooklyn, N. Y.	Super highway	Deck girder	1 @ 91	.....	...
	Bay Parkway Bridge, Shore Parkway, L. I., N. Y.	Super highway	Skew deck girder	1 @ 85	82	146

1939	Bridge No. 74, Grum Falls, Schoharie County, N. Y.	Highway	Low truss	1 @ 88	.....	...
	Lake Piseco Outlet, Hamilton County, N. Y.	Highway	Low truss	1 @ 88	.....	...
1940	Two duplicate structures in Main Ave. bridge approach, Cleveland, Ohio	Elevated highway	Rigid frame	30–70–30	40	...
	Naugatuk River Town of Seymour, Conn.	Highway	Rigid frame	1 @ 58.5	35	...
1941	Antler Bridge, Central Valley Power Proj., Calif.	Highway	Continuous truss	(Shop welded only)		...
1941	San Sebastian River crossing of Florida East Coast R.R. at St. Augustine, Fla.	Railway	Continuous steel beams on steel pipe pile bents	18 @ 12 ft. 9 in. and 2 @ 10 ft. 0 in.	Double track	100 tons (exclusive of 3680 ft. of piling)

welded, attention might be directed to the following parts of the 2800-ft span Tacoma Narrows Bridge, 1939–40:

(1) the plate eyebars with welded "eyes" used in the cable anchorage in lieu of the forged-head bars previously typical;

(2) the heavy plate weldments used as cable saddles, on top of the main towers, in lieu of steel castings which always have been a difficult foundry problem;

(3) the welded plate cable bands, clamping around the cables for support of the wire-rope floor suspenders, another casting replacement.

Despite the terrific punishment which this bridge underwent, before its collapse under oscillations due to wind, all of these welded details held with perfect integrity.

The railings of highway bridges are welded today with virtually no exceptions.

Economy

The economies that may be gained through the use of welding result mainly from decreased quantities of structural steel in members and connections; elimination or reduction of punching, drilling and handling operations; reduction of corrosion and of cost of painting and maintenance. For curved members, a considerable amount of blacksmith work and straightening is eliminated when welded flange plates are used.

As in other classes of fabrication, care must be exercised to avoid a reduction of weight of material at the expense of such an increase in cost of fabrication as to more than offset the saving in material, unless other definite advantages are realized.

The smoother lines and surfaces that result from welded construction have been accorded an architectural preference in many classes of bridge structures.

Degree of Acceptance

The applications in which welding for bridges has met with the widest acceptance have been governed largely by economy and by a rather common policy of progressing from the use of welding for less important details to its use in a more responsible role; and also by the exigencies of special circumstances, in the case of repairs, strengthening and alterations. The lack of funds for new construction has often led to the use of welding as the only practicable method for keeping bridges in service or increasing their capacity for heavier traffic. In many instances important welded joints have had to be made under circumstances that rendered the welding much more difficult than in new construction, in which the weldability of the steel can be wholly assured, and the details of the joints and sequence of their welding can be arranged to the best advantage.

As bridge engineers and steel fabricators have become more familiar with the proper control of welding, and as more information has been developed through research and experience, more and more reliance has been placed upon welding, until now there are even instances of beams and girders being spliced by means of butt welds.

One of the most popular uses of welding for main members of new bridges in America has been for the attachment of cover plates to rolled beams, especially in continuous bridge and viaduct construction, because of the cost savings effected through reduced cost of fabrication as well as the reduced weight of steel made possible by utilizing the full gross section of beam flanges and cover plates.

The greater popularity of welding for plate girders than for bridge trusses reflects the greater opportunity for cost saving that has been afforded in the former class of members as a result of adopting details especially suitable for welded fabrication.

Many of the welded bridge trusses that have been constructed have been merely riveted designs with welds substituted for rivets, and the welded truss may be expected to gain ground more rapidly when welding-minded designers develop design and erection procedures more closely in line with fundamental principles of welded construction.

E—JOINTS

Permissible Joints

The A.W.S. Bridge Specifications permit butt, fillet, plug and slot welds in general, and if these conform to the standardizing requirements set up, they require no qualification of procedure. Change of the art is in nowise interfered with, as non-standard joints may be used if proved to be suitable by stipulated qualification tests.

Non-permissible Joints

The Specifications forbid the use of saddle welds (except for sealing), of intermittent butt welds, and of butt welds made from one side only without backing material.

Prequalified Joints

Prequalified butt welds embrace Single and Double Vee, Bevel, J and U grooves; also square-edge in material up to $1/4$ in. Prequalified details thereof embrace limits of maximum plate thickness and minimum included angles, root face, opening and radius, and surplusage of contour. Alternative procedures are approved for transition butt welds between parts of unequal thickness. Butt welds made on a backing, rather than welded from both sides of the groove, are penalized 15% in unit stress.

Fillet welds may not be of less than stipulated minimum leg sizes, related to the thicker material joined. Spacing and arrangement of fillets are regulated with a view to reducing stress concentrations where they terminate.

Butt vs. Fillet Welds

The unit stresses permitted on fillets and on base material connected by fillet welds are so penalized as compared with butt welds as to necessarily encourage the use of the latter. This is intentional, as all joint research has shown the superior resistance of butt welds to repeated and reversing

stresses on account of the smoother stress paths. Moreover, present test results on fatigue of butt welds are more consistent and dependable than those on fillet welds. Although the tendency of detailers, following riveted precedent, has been to use fillet-welded lap connections, it is the duty of the bridge specification to encourage the more efficient butt type. A strong preference is accorded to continuous, rather than intermittent fillet welds, out of consideration for fatigue strength as well as resistance to corrosion.

Plug and Slot Welds

Plug and slot welds are permitted to carry calculated shear at the unit values for fillet welds in shear; they may not carry other types of calculated stress. The holes or slots may be filled in a continuous welding operation, but uneconomical filling is not required. Diameter of hole, or width of slot, if of the filled type, may not exceed $2^1/_4$ times the plate thickness.

Web and Flange Splices

Quite early in the development of welded bridge design it was realized that fillet-welded strap splices for webs and flanges of girders are much less efficient than butt-welded splices. The unit stress provisions of the A.W.S. Bridge Specifications reflect this advantage and these specifications have now dropped a former restriction against the use of butt welds for splices in tension flanges. However, they stress the necessity for employing a carefully controlled procedure and sequence of welding for making welded splices in rolled beams and built-up girders, to insure against serious shrinkage stresses and deformations.

The specifications require that all shop splices in each component part of a built-up member be made before such part is welded to other parts of the member. In making butt-welded splices in rolled shapes and in making butt-welded field splices in built-up sections, the sequence and procedure of welding must be such that while the weld and the heated base metal are contracting at any point, any parts of the member that would furnish restraint against such contraction can move, shrink or deform enough to prevent the shrinkage of the heated metal from producing harmful effects. As an example of such provisions there is cited the welding of the thinnest element (usually the web) prior to the welding of the thicker elements; also the use of "step-back" sequences, and the use of preheating under some circumstances.

The most common practice is to use double V butt welds for all web splices, and for shop splices in flange plates except where double U joints are more economical. Single V or single U butt welds with a shallow groove for back welding are used for field splices of flanges to minimize the amount of overhead welding.

F—TESTS AND INSPECTION

Safety

The safety of bridge construction depends upon adequate laboratory testing to afford a basis for design, and adequate job inspection to enforce the necessarily high standard of workmanship.

Static and Fatigue Research

The static testing of welded joints has proceeded far enough to give designers as accurate knowledge of the factor of safety of a proposed bridge connection under static loading conditions as they would have with riveted or bolted construction. Such conditions, unfortunately, do not prevail in railway bridges, or in highway floors and short-span highway bridges. Here our designers do not, as yet, know with any certainty the stresses which their members and connections can resist through the necessary thousands or millions of repetitions of the critical cycle. Here such knowledge as we have is borrowed from abroad, but is being rapidly augmented by the work of Committee F, Fatigue Testing (Structural) of the Welding Research Committee of The Engineering Foundation.

Committee F is nearly ready to publish adequate data on the fatigue strength of butt welds, including position of welding as a variable. It is investigating the diameter–thickness ratio of plug welds, as affecting fatigue strength. It is studying the possibility of restoring the rivet-hole loss of section in riveted tension members, by welded reinforcement. It has thus far found disappointingly low fatigue strengths for the forms and arrangements of fillet-welded connections that have been investigated and is seeking to evaluate improved forms, for use where butt welds are impracticable. The work of this Committee is directly correlated to the Society's Bridge Committee, and ultimately will lead to more accurate and economical proportioning of welded bridges.

Safeguards

Non-destructive testing has never been found to be practical in connection with any American methods of bridge construction. In the case of welding, reliability is predicated upon the establishing of suitable welding procedures, the qualification of welding operators, and adherence to the provisions of the established procedures and to the general workmanship specifications.

It is of foremost importance that welding contractors have their work and personnel organized under competent supervision, to coordinate all operations of fabrication and erection to the end that suitable conditions for welding will result, and corrections will not have to be made.

Job Inspection

The engineering inspector on welded construction should, of course, perform the same duties as required for other classes of steel construction to determine that all materials are acceptable, dimensions are correct and the fit-up at joints is good. He must satisfy himself that the work has been planned in advance and is properly organized under competent supervision to follow an established procedure and sequence of fabrication and welding. He must ascertain that the welding operators have all been properly qualified for the work they are to do, and he must check on each operator to see that he understands the established procedure and is following it; also to make sure that he is in good physical condition.

Continuous inspection of every operator is not necessary; occasional ob-

servation, together with a careful check-up on finished welds, has been found adequate, if previous duties as outlined above have been exercised.

The finished welds should be checked for agreement with the plans and specifications, as to size, arrangement, surface contour or convexity, and absence of defects such as cracks, undercutting, overlapping, objectionable irregularities, unfilled craters, pock-marks and other defects. In the case of highly responsible butt welds, especially those subjected to tension, particular attention should be given by the inspector to the checking up of groove dimensions and spacing, prior to welding. Under some circumstances, continuous inspection of the welding of such joints is necessary, to make sure that the slag is carefully removed between deposition of layers, that the maximum allowable thickness of layer is not exceeded, that the root is thoroughly cleaned and chipped or gouged out before welding is started on the opposite side of the groove from that on which the first pass was made, and to see that other provisions of the welding procedure are strictly followed.

CHAPTER 37

MACHINERY CONSTRUCTION*

Economics of Welded Construction, Welding vs. Casting, Appearance, Improved Product and Delivery, Cost Savings, Materials, Type of Materials Suitable, Use of Plates, Use of Structural Shapes, Use of Pipe and Tubes, Use of Steel Castings, Design Details, Stress Analysis of Joints, Stress Concentrations, Residual Stresses, Tolerances for Machining, Fabrication Problems, Distortion, Use of Welding Fixtures, Preheating, Fit-up Tolerances, Joint Rigidity, Stress Relieving

ECONOMICS OF WELDED CONSTRUCTION

FUSION welding is important in machinery construction because it makes possible the economical substitution of structural steel for cast iron in many structures, it eliminates pattern costs in cases where castings are replaced, it speeds up production, it makes possible a distribution of material based only upon load conditions, and it produces joint efficiencies superior to those obtainable by bolts and rivets.

In some cases, as where the design is simple, welded construction has a wide margin in cost over cast metal construction, and in such cases refinements in design which effect savings are not so necessary. Increased competition both from welderies and foundries, however, is making it necessary to carefully design every welded product in order to make it economically practical. In addition, the increased use of welding on new equipment and under more severe working conditions makes it necessary for the designer to be thoroughly familiar with the physical characteristics of welded joints.

Welding vs. Casting

Structural steel is approximately five times as strong in tension, two and one-half times as stiff, and costs about one-third as much per pound as grey cast iron.

A member which is designed on the basis of tensile strength requires a steel section one-fifth as large as a cast-iron section. The steel costs approximately one-third as much per pound as the cast iron, consequently

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the material cost of the steel member will be about 7% of the cast-iron member having an equivalent load-carrying capacity.

If instead of tensile strength the important characteristic is stiffness, as is often true of machinery parts, then it may be necessary to use only 40% as much steel as cast iron for the same support in order to obtain the same rigidity. Since structural steel costs only one-third as much per pound as cast iron, the material cost of the steel member will be approximately 13% of a cast-iron section having an equivalent stiffness.

Care must be taken in the application of this rigidity ratio in actual design work, since only those areas which are axially loaded can be reduced by any such amount. In the re-design of members subjected to bending, it is the moment of inertia that is reduced by 40%, and this new value is used in the re-design of the section.

The greatest handicap in substituting welded rolled steel for castings is the so-called conservatism of the design engineer. The use of a cast structure as a model is a common fault. Obviously this is neither good engineering nor good economics. The designing engineer should entirely eliminate from his mind the appearance of the old structure and resolve it into its component parts with its needed functions. If this is done, a better and more economical design will be developed.

Appearance

The appearance of the new structure will be different from the old one and should be. In some cases the appearance will be so radically changed that it will be surprising, but after a time the new structure will usually be more attractive than the old.

Engineers are accustomed to seeing round corners and sloping sides on cast structures and unless they are present the appearance seems objectionable to many. These round corners and sloping sides are not used for strength requirements but are essential in order to draw the pattern from the sand mold. This handicap of castings is not present with welded structures and an appearance similar to a casting is often difficult to obtain and generally results in excessive costs. The sharp corners and the straight and more rigid sides which the welding design gives should be incorporated with its very much lower cost. The original objection to this changed appearance will rapidly disappear as experience grows.

Improved Product and Delivery

Considerable expense is saved over castings by the elimination of patterns, pattern drawings, pattern storage and the delay incident thereto. When only one structure is to be made, the pattern cost is frequently greater than all the other costs that go into the structure. Many times a welded structure can be fabricated in less time than it takes to make the pattern for a casting. This condition greatly speeds up production and delivery.

A welded structure made from rolled sections normally contains sound metal throughout. The problem of blow-holes, draw and shrinkage cracks is eliminated. This condition insures a more uniform product and eliminates

the danger of scrapping parts after they are partially machined and a blowhole or porous area is uncovered at a critical section.

Cost Savings

The cost saving obtained by re-designing for welding varies with the type and size of structure and the ingenuity of the designer. Experience has shown that in certain cases cost savings of approximately 50% over previous cast-iron structures can be obtained if the designer will attack the problem with an open mind and the objective of developing an original design. However, there are some applications for which castings are most suitable.

MATERIALS*

A great variety of materials is available for use in welded construction, such as billets, slabs, structural shapes, plates, bars of all descriptions, pipe, forgings, special rolled sections and steel castings. There is a great difference in the price per pound of these materials and certain facts regarding their surface, size, cutting tolerance, etc., have an important bearing on their use. Therefore, it is not only important for the designer to consider rolled steel sections but also to consider such sections in sizes and shapes that will take the base price or as few extras as possible.

Steel companies publish pamphlets listing extras and deductions, quantity differentials, and standard tolerances in thickness, width and length for various rolled steel products. Variations from true flatness are also published and extras for special flatness are quoted on application. It is essential that the designer be familiar with these data in order that he may use the cheapest possible material and still get the proper steel for the purpose.

When using plates for machine construction there are a few things in particular the designer should keep in mind. Up to and including 2 in. in thickness plates are sheared and there is no charge for cutting. Plates over 2 in. in thickness are flame cut for which a charge is made, according to thickness. However, because of possible "shear warp" flame cutting is recommended where possible.

The universal mill rolls plates to exact width, within usual mill tolerances, (rolls steel in one direction only), consequently on plates over 2 in. in thickness the customer is charged for only two flame cuts (such plates are obtainable in widths up to about 60 in.). Plate mills roll steel in both directions and in much wider widths but the customer is charged for four flame cuts on plates over 2 in. in thickness.

When purchasing steel it is often uneconomical to order individual items cut to size. When two rectangular pieces of the same width are ordered as separate items, and they are made on a universal mill, the customer pays for four flame cuts across the width of the piece. If the two plates are combined and ordered as one piece, however, the customer pays for only

* A considerable portion of this section has been taken from Chapter 52 on "Economy in Welded Machinery Design," by H. G. Marsh, A. W. S. Handbook, 1938 edition.

two cuts across the width of the piece, the third cut being made in the customer's shop.

Plates which are not rectangular in shape are called sketches and take a per pound extra based upon the number and shape of the cuts required.

The designer should also bear in mind that flame-cutting tolerances on a 3-in. plate is plus $^5/_8$ in. This tolerance is often not small enough for the user and extra cost is involved in additional cutting or machining by the purchaser before the plate can be used.

There are many opportunities to use semi-finished material such as billets, blooms or slabs in machine construction. Billets have rounded corners which might prevent them from being used for some purposes, but for many others they will serve very well and the finish will not be objectionable.

The surface of slabs is not suitable for machine construction unless the part is to be machined or is in an inconspicuous place, for slabs usually contain roll ragging marks.

Straightness must also be considered in semi-finished material if the pieces are in long lengths because this material is primarily intended for re-rolling and is not required to be straight. Semi-finished material is low in price, and where it will serve the purpose, its use presents an opportunity for reducing the material cost.

Type of Materials Suitable

There are many grades and types of steel and non-ferrous metals that can be satisfactorily used in the construction of welded machinery.

The major portion of all-welded machinery is fabricated from materials containing less than 0.30% carbon. Material of this grade has satisfactory physical properties and is readily welded and flame cut.

Many special low alloy steels are also available which have welding properties comparable to the plain low carbon steels. These alloys have higher

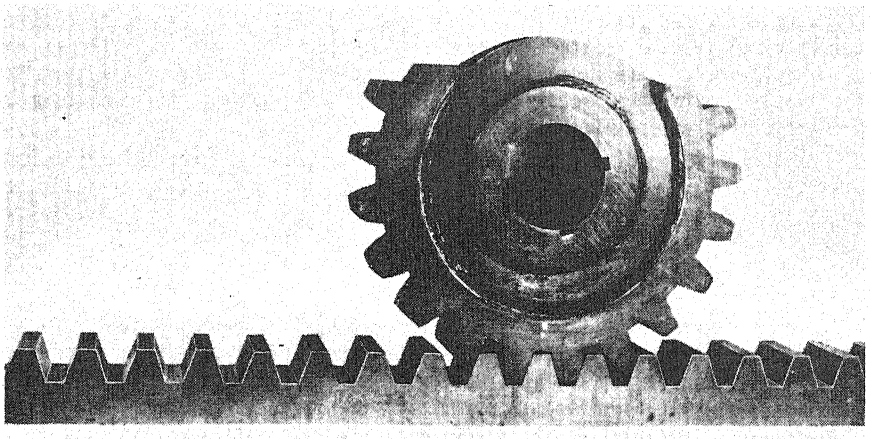


Fig. 1—Gear Fabricated by Welding

tensile and yield strength than plain low carbon steels and generally have somewhat better corrosion-resisting properties. It is important to remember, however, that the modulus of elasticity of all steels is approximately the same, consequently where deflection requirements are the design criterion, the higher strengths of the more expensive low alloy steels are of little importance.

Many high alloy and medium carbon steels are being incorporated in machinery designs with excellent success. Knowledge of the weldability of such materials is essential, however, in order to properly design the joints and to satisfactorily fabricate the structure. Figure 1 illustrates a gear ($^1/_2$ diametral pitch, 10-in. face, 32-in. P.D.) fabricated by welding an S.A.E. 4140 forged rim to a mild steel plate and hub. The parts were preheated with a gasoline torch to 600° F. before the rim was welded and after welding was begun it was continued to completion without interruption. This gear is operating successfully and delivers over 17,000,000 in.-lb. torque.

Non-ferrous materials such as nickel, Monel, bronze, etc., are also incorporated into machinery designs. Problems of expansion and welding technique are of particular importance in such structures.

Use of Plates

The general use of plates for machinery parts needs no comment. One point the designer should always keep in mind, however, is the economy obtained by forming plates around corners in order to eliminate welding. For example, a rectangular section made by welding four plates together requires four separate welds. The same result might be obtained by bending two plates into angles before welding, which would require only two welds. In some cases three corners could be bent, thereby requiring only one weld. Special channels are also more economically made by bending a plate than by welding three plates together. Box sections can be made from such channels by welding closing flanges to them.

Formed sections of this type not only afford economies by reducing the amount of welding but also produce rounded corners which in some cases are still considered essential for good appearance.

Use of Structural Shapes

Structural shapes have a definite field in machinery construction and should be used to the fullest extent. In many cases their use appears to be limited probably because the designers have not yet learned to think in terms of rolled shapes as much as they should or because they are not familiar enough with the variety of shapes available. In many welded structures, sections that can be obtained as rolled shapes have been built up of welded plates. This means considerable flame cutting and welding, whereas many of the rolled sections can be purchased at about the same price per pound as the plate.

Generally speaking, a rolled section is cheapest, a formed section made by bending plates is next, and a welded section is the highest priced. For example, a rolled channel is cheaper than one formed by bending a plate into a channel, and a bent or formed channel is cheaper than one welded

from three plates. A rolled I-beam is also cheaper than one formed by welding three plates.

Box sections which are excellent for resisting stresses of a complex nature are readily fabricated from pairs of angles or channels. The wide range of size of structural members available makes it unnecessary to use formed plate sections except for large size parts.

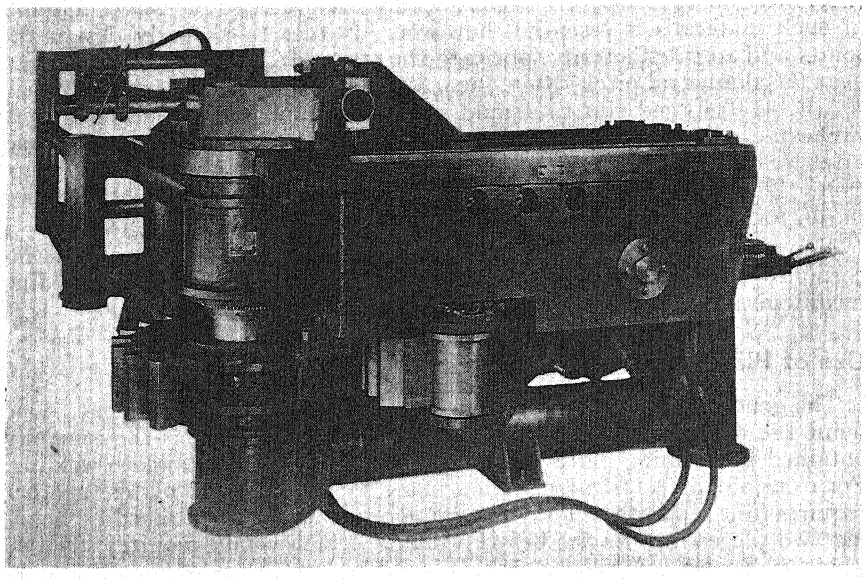


Fig. 2—Rotating Bending Machine Fabricated by Welding

Use of Pipe and Tubes

One of the most efficient sections available to the welding designer is the pipe or tube. A tubular member has the same resistance to stress in all directions because of the central location of its neutral axis. For resistance to torque, nothing compares dollar for dollar with a tubular section and it may be easily joined to any surface shape by welding.

An example of the use of tubular sections is the eccentrically loaded mandrel extension unit and frame of a rotary bending machine built to bend 12 to 17 in. O.D. pipe, as illustrated in Fig. 2. It is estimated that the use of tubing rather than box or H-beam sections for this structure reduced the weight 22,000–27,000 lb. and the labor 168–198 man-hours.

Use of Steel Castings

The combined use of steel castings and rolled sections has proved economical in certain cases. Complicated sections which would require a number of parts and a large amount of welding are often more economically made by casting. This is particularly true if there are a great many parts to be made.

Other cases where the use of castings has been advantageous is in the construction of large bosses and bearing blocks for gear cases which otherwise would have had to be cut from large blocks. Figure 3 illustrates a fabricated gear case containing cast steel bearing blocks.

DESIGN DETAILS

The service life of any welded machine is dependent upon the proper design of the various members and the joints between the members. From a welding viewpoint the joints are the important factor, consequently it is important that the designer be familiar with characteristics peculiar to the different types of joints used.

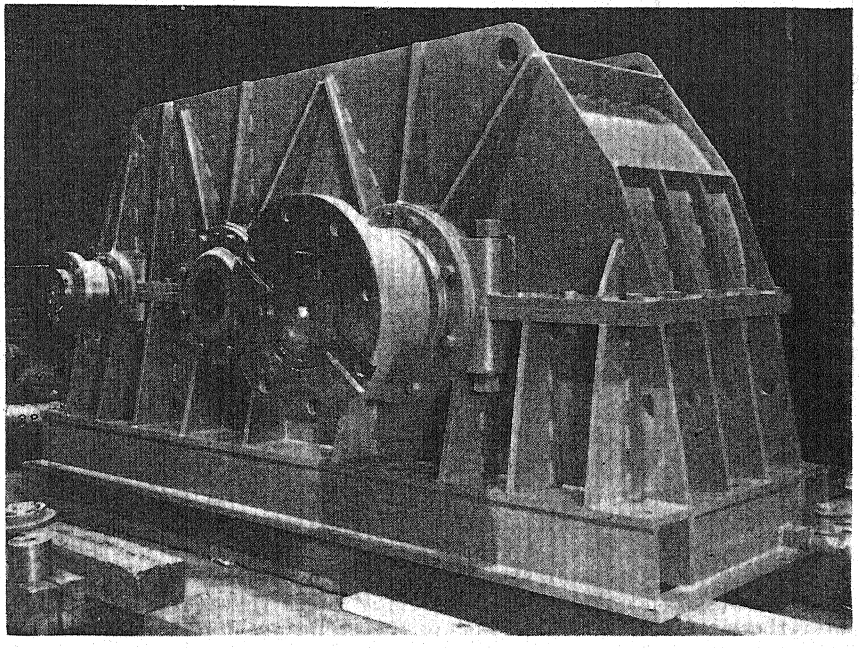


Fig. 3—Fabricated Gear Case Containing Cast Steel Bearing Blocks

Stress Analysis of Joints

Two general types of welds are used in making strength joints on machinery—grooved welds and fillet welds.

Tensile and shear stresses for grooved welds are usually calculated by dividing the force by the cross-sectional area of the weld. Maximum bending stresses are calculated by dividing the bending moment by the section modulus of the weld. When a combination of tensile, shear or bending stresses is present, they all must be taken into consideration in the usual manner.

Fillet welds are generally considered to be stressed in shear regardless of

whether the load is applied parallel or transverse to the weld axis and the stress is calculated by dividing the force by the weld throat area (weld throat = 0.707 × weld size). If a fillet weld is subjected to a combination of shear and tensile stresses acting at right angles to each other, the resultant stress may be considered the vector sum of the two stresses (Fig. 4).

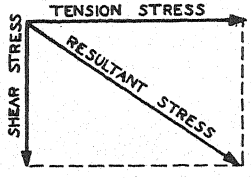


Fig. 4.—Vectorial Addition of Stresses in Fillet Welds

Stress Concentrations

Local discontinuities and abrupt changes in the section of a member cause a local bunching of the stresses (stress concentration) at these points and are usually known as stress raisers. The importance of stress raisers and the resulting stress concentrations are dependent upon the ductility of the material and the type of loading.

Stress concentrations in ductile materials subjected to static loads are generally not serious because the metal can yield or flow plastically to neutralize or redistribute the stress. Brittle materials will not flow plastically, consequently there is no redistribution of stress and there is danger of failure occurring at points of stress concentration.

Stress concentrations in members subjected to fatigue loading may produce failures and should be avoided or properly taken into consideration when calculating the size of the member.

A fatigue failure in a machine is governed by two factors: the ability of the material itself to withstand repeated stresses and the existence of points at which the stress exceeds the endurance limit of the material. Stress raisers resulting from sharp corners, fillets, notches, holes, etc., may produce stress concentration factors many times the average stress and unless these peak values are held below the endurance limit ultimate failure in service will result.

In order to prevent fatigue failures from stress concentration, two methods may be used:

1. Eliminate as nearly as possible the stress raisers or causes of the stress concentration.
2. Design the member so that the maximum stresses obtained at the points of stress concentration do not exceed the endurance limit.

Welded joints, because of their character and shape, are often stress raisers. A small hole in a plate will produce a theoretical stress concentration of 3 to 1 and a small gas-hole or slag inclusion is not uncommon in welds. Sharp corners and notches are well-known stress raisers and are obtained with groove welds having incomplete penetration, at the heel and toe of a fillet weld, and at points of undercut or reinforcement.

Welded joints on machinery subjected to dynamic loads should be designed with these factors in mind. Stress raisers resulting from the weld's shape should be eliminated as much as possible and high-quality welding should be used.

Residual Stresses

The process of welding is known to produce residual stresses which may reach in magnitude the yield strength of the material. If the structure is loaded in the same direction as the residual stresses, it is apparent that there will be plastic yielding and the actual stresses may greatly exceed the design working stresses.

Residual stresses are also known to cause a structure to warp and twist out of shape during machining because of their redistribution as the outer layers of metal are removed. Instances are known where residual stresses have caused structures to creep badly out of shape over a period of several years in service.

Stress relieving by heat treatment will practically remove residual stresses and prevent the above-mentioned difficulties.

Tolerances for Machining

The process of welding is accompanied by a certain amount of shrinkage and distortion. In addition, rolled sections, plates, castings and formed parts are supplied with certain tolerances. In order that the finished product may meet the required dimensions it is essential that all of the above factors be taken into consideration.

Tolerances on rolled sections and formed parts are easily obtainable but it is impossible to give exact values to be allowed for distortion. The distortion obtained during welding is a function of the joint design, the amount of welding, the welding process, the position of welding, the fit-up of the parts and the use of fixtures, clamps, etc.

Tolerances on parts that are to be machined, based on many years of experience with fabricated machinery, are as follows:

1. Small parts containing very little welding—$^1/_8$ in.
2. Moderately large parts containing a small amount of welding—$^1/_4$ in.
3. Large structures containing moderate amounts of welding—$^3/_8$ in.
4. Large complicated structures and structures containing large amounts of welding—$^3/_8$ to $^1/_2$ in.

FABRICATION PROBLEMS

The economic advantages obtained from a welded structure are partly dependent upon the cost of fabrication. It is important, therefore, that considerable effort be spent in simplifying the manufacturing process, insuring that the welding is done properly and in eliminating unnecessary fit-up time and objectionable distortion.

Distortion

The importance of distortion depends largely upon the part being fabricated. In any case it is objectionable and often results in an undesirable straightening expense. The design and fabrication process should be worked out to reduce this trouble to a minimum.

The fact that distortion is the result of welding indicates that the amount of welding used should be held to the minimum that is consistent with the loads carried.

Excessive welding on one side of the neutral axis of a member will also produce undesirable distortion. Balancing the welding as well as possible is often desirable.

Properly tack welding the parts together or holding the assembly in place by clamps or fixtures will be helpful in maintaining the proper shape of the structure.

Poor fit-ups tend to produce excessive distortion.

In many cases distortion is compensated for by preforming the parts out of shape and permitting the deformation caused by welding to pull the structure back into the desired shape. Assembling the parts slightly oversize and permitting them to shrink to the desired size is often advantageous.

Use of Welding Fixtures

The use of welding fixtures to aid in the fabrication of welded machinery has many advantages. In general such fixtures are used for the following purposes:

1. Locate parts during assembly.
2. Hold parts in alignment during tacking and welding, thereby reducing distortion.
3. Position the structure to facilitate welding in any desired position.

Fixtures that are used primarily to prevent distortion must be more rigid than the structure itself, otherwise the fixture will distort and the desired result will not be obtained. To eliminate distortion of the structure when it is removed from the fixture the practice of stress relieving by heating the combined assembly before separation is sometimes used.

Preheating

Preheating machinery parts before welding is seldom done, except in special cases.

Parts made from special steels that will harden during welding should be preheated to insure sound welds and to reduce hard areas at the fusion line which might develop cracks or produce machining difficulties.

Structures made from heavy members are often preheated, even though the carbon content is low, because this treatment helps prevent weld cracks and aids in reducing distortion.

Fit-up Tolerances

Proper fit-up of all parts is essential in a structure. Wide gaps and poorly fitting members generally produce excessive distortion and require the deposition of excessive amounts of weld metal in order to make welds of the proper strength.

Fillet welded T-joints should be assembled so that metal-to-metal contact is obtained if possible. Except for designs requiring machining or some other specific means of insuring metal-to-metal contact or a very small reasonable gap a maximum tolerance of $^3/_{32}$ in. is often allowed for processing reasons. In special cases gaps up to one-half the thickness of the thinner member but not exceeding $^3/_{16}$ in. are allowed, providing means are taken to insure that the weld joint is equivalent in strength to that required by the design.

Fillet welded lap joints should have metal-to-metal contact if possible and the gap should not exceed $^1/_8$ in. unless the weld size is increased to compensate for this gap.

Corner joints should be assembled so that the gap between the butting corners does not exceed one-half the thickness of the thinner plates but in no case more than $^1/_8$ in.

Butt joints should be prepared and fitted up in accordance with the process specification governing the welding.

Joint Rigidity

Rigid joints are difficult to weld and may cause trouble from cracks resulting from the development of high residual stresses. Such joints should be avoided wherever possible, either by proper design or by the use of the proper welding procedure.

Stress Relieving

The most effective way to reduce residual stresses is by thermal treatment. The general practice followed in stress-relief heat treatment consists of slowly heating the structure to 1100–1200° F., allowing the structure to soak at the heat-treating temperature for at least one hour per inch of thickness of the thickest member welded and slowly cooling the structure again.

Heat-treating temperatures higher than 1200° F. are sometimes used in order to obtain grain refinement as well as stress relief.

The value of and need for the relief of welding stresses is open to question but experience indicates that it is advantageous under certain conditions, such as: (1) structures subjected to dynamic loads, (2) structures which must accurately maintain their shape during their service life, (3) structures composed of heavy members and rigid joints which probably contain high residual stresses.

CHAPTER 38

PRESSURE VESSELS AND BOILERS*

Development of Welding for Boiler Drums and Pressure Vessels, Advantage of Fusion Welded Construction, Adoption and Requirements of Codes and Specifications, The Effect of Welding on Design, Materials Used in Construction, Fabrication—Shop Practice

UNDER this classification are included all vessels used in the various industries and drums for power boilers. Such vessels usually consist of closed cylindrical shells which are subject to an internal pressure and are designed to withstand safely a certain maximum stress under operating conditions. Although the problems encountered in fabrication and welding are essentially similar, there are two generally recognized types of pressure vessels, those that are classed as unfired pressure vessels, and those that are classed as boilers.

Steam boilers are, as a class, operated at lower maximum temperatures than many pressure vessels used in the oil refining and chemical industries. The steam and water drum of a boiler may be heated to the temperature of saturated steam (approximately 700°F. maximum, but generally much lower depending upon the operating pressure) whereas, an unfired pressure vessel in one of the process industries may be subjected in service to a temperature as high as 1000°F. Steam is sometimes superheated to as high a temperature as this, but the superheater drums are of a smaller diameter than the steam and water drums and are, therefore, more readily constructed.

In view of the stresses introduced in service by the pressures and temperatures of operation, it is apparent that a hazard is involved in the failure of an inadequate or defective part. Safety codes have, therefore, been prepared to cover the construction of all drums for power boilers and for pressure vessels.

Development of Welding for Boiler Drums and Pressure Vessels

Earlier Methods of Manufacturing.—Before fusion welding had reached its present high degree of development, the use of welded joints was naturally and properly limited by various safety construction codes. Fusion

* Prepared by a committee consisting of M. Christensen, Babcock & Wilcox Co., *Chairman;* T. M. Jasper, A. O. Smith Corp.; A. J. Moses, Combustion Engineering Co.; C. W. Obert, The Linde Air Products Co.; J. T. Phillips, Foster Wheeler Corp.; D. B. Rossheim, M. W. Kellogg Co. Parts of the material on Unfired Pressure Vessels, including Figs. 1 to 5, are taken from the chapter that Mr. T. M. Jasper prepared for the 1938 edition of the Welding Handbook.

welding the main joints of boiler drums was not permitted and the construction followed the older conventional methods of (1) riveted, (2) forge and hammer welded and (3) forged seamless drums.

Limitations of Earlier Construction Methods.—The mechanical limitations and the undesirable stress characteristics of a riveted joint restricted its use to drums of approximately $2^1/_2$-in. wall thickness as a maximum.

Forge and hammer welding, although eliminating the mechanical joint, was also limited to a plate thickness of approximately 2 in. maximum due to difficulties encountered in obtaining thorough fusion at every point in the weld in thicker plates. Furthermore, for successful forge and hammer welded construction, a low carbon steel was necessary. The maximum working pressure of such drums was restricted by the combination of low tensile plate and a limiting wall thickness.

The limitations imposed by the riveted joint and the forge and hammer welded joint very definitely restricted their application to relatively low pressures and temperatures, and made it necessary to use very costly forged seamless drums to meet the more severe service requirements imposed by developments in power plant design and industrial processes.

The most probable solution to this economic problem was the refinement of existing fusion welding processes of joining the edges of rolled or pressed plates to the point where such methods would satisfactorily meet fairly rigid requirements, avoid the thickness limitations imposed by riveted or forge welding construction, and would be less costly than seamless forged construction. Of the several fusion welding methods which in previous years had been developed to a limited degree of satisfactory performance, the metallic arc welding process was the first developed for welding boiler drums and similar types of vessels.

The quality of welded seams in pressure vessels and the efficiency of the welding technique followed were largely indeterminate inasmuch as existing test methods consisted primarily of determining the physical properties in welded test specimens. This method of testing obviously could not assure uniform weld quality in the pressure vessel even though the same welding technique was used in both test weld and main welded joint.

In preliminary work, full-sized welded vessels were tested to destruction, and it was demonstrated that welded joints of satisfactory quality could be obtained. This again failed to give assurance that all joints in subsequent vessels are of satisfactory quality.

Requirements for the Successful Application of Welding to Boilers and Pressure Vessels.—The question of substituting welded construction for older fabrication methods, therefore, resolved itself into the twofold problem: that not only was it necessary to develop a satisfactory welding technique, but it was obviously necessary that some means be provided whereby manufacturers, users and control agencies could be given assurance of satisfactory performance. It was evident that universal approval of welded construction for pressure vessels depended upon fulfillment of the following basic requirements:

1. The physical properties of the weld metal should compare favorably with those of the plate material with respect to ductility, tensile strength, impact resistance, corrosion resistance and endurance or fatigue limit.

2. The joint as a whole should possess satisfactory physical properties and show no tendency to localized weakness in the base metal-weld junction, nor in that portion of the base material affected by the heat of fusion.

3. A non-destructive test method should be used to supplement the otherwise inadequate physical tests obtained on weld test specimens by which a welded joint could be examined to reveal the presence of injurious defects such as excessive porosity, entrapped slag, non-fusion and cracks.

All of these requirements are embodied in the rules of the Bureau of Engineering of the Navy Department and in the A. S. M. E. Code which require the main fusion welded joints of power boilers to be radiographed. The A. S. M. E. Unfired Pressure Vessel Code and the A. P. I.-A. S. M. E. Code also embody all of these requirements.

Physical Properties of Weld Metal and Welded Joints—Heat Treatment.—Certain structures which are subject to severe impact loads call for welds having good energy absorbing qualities. Ductile welds should be used for ductile steel structures. A good rule to follow is that the characteristics of the weld (strength, ductility, toughness, etc.) should be substantially equal to or slightly better than those of the steel welded. With correct filler metal, expert welding technique and the proper steel, this can be readily accomplished. In applying welding, the designing engineer, therefore, need only specify appropriate requirements covering the welds of the structure. Improvements in existing welding processes, particularly in metal arc welding eventually resulted in the production of strong, ductile and tough weld metal.

Figure 1 graphically illustrates findings from tests made on specimens cut parallel to the weld joining $2^5/_8$-in. steel plates. Each point on the curves represents a test bar the full thickness of the plate and on 1-in. spacing. The area thus covered extends 6 in. to each side of the weld. The curves for ultimate strength and yield point show gradual increases through the areas adjacent to the weld, reaching their peaks in the center of the weld.

Toughness of the weld as compared to that of the plate material is indicated by the following typical results of Charpy impact tests on the same steels as used for the test illustrated by Fig. 1. The average value obtained on the standard keyhole bar is 25 ft.-lb. for the plate material, and 30 ft.-lb. on good quality weld metal. The values obtained for the weld junction and the adjacent metal were between the above-mentioned values.

It might be well to again emphasize the importance of proper welds. While small inequalities in characteristics between the weld and the plates welded may not give trouble, serious consequences may result from poorly designed welds. For instance, failure can occur in a strong but brittle weld before the plate material has reached a stress much above the yield point. Why this can happen is explained by Fig. 2, which is a stress-strain diagram for a ductile steel, a ductile weld and a brittle weld. As an example, consider a condition which frequently exists, where a weld joining two plates is stressed in a direction parallel with the joint. The strain on the weld will then be the same as on the plates and, if brittle, the weld material cannot elongate as much as the plate material. The result is that the weld may reach its breaking strength when the plate steel is stressed only to a little over half of its ultimate strength. This is indicated by points A and A', respectively. In other words, if the structure is de-

signed with a theoretical safety factor of 4, based on the weld separately, then the real safety factor would be only a little over 2. Should the strain be allowed to reach point A, the weld would fail as indicated in Fig. 3 due to lack of ductility but not for lack of strength. Needless to say, such a fracture has a tendency to progress once it is started.

However, had the weld been of proper ductility—again referring to Fig. 2—the strain in the structure could have been carried to points B and B',

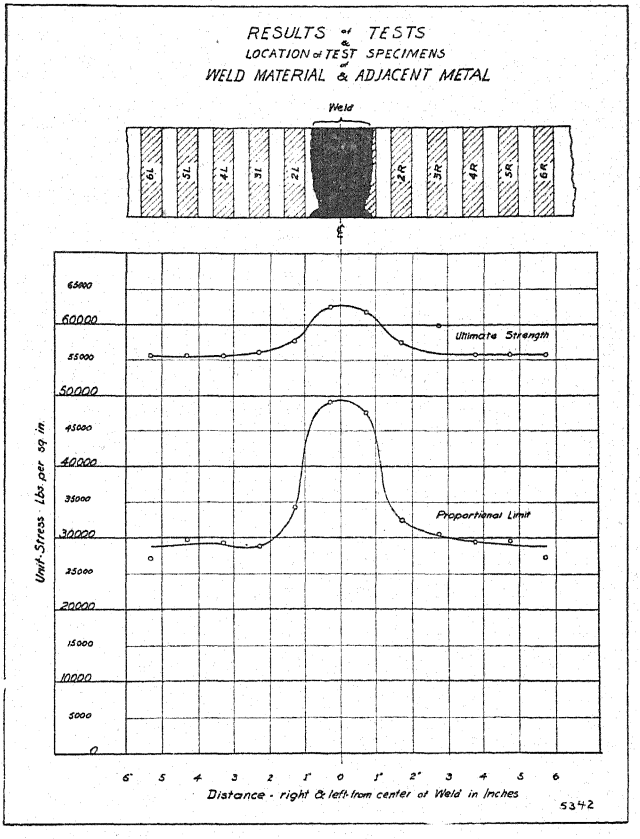


Fig. 1—Test Results on Specimens from Welded Plates $2^5/_8$ In. Thick Showing That the Weld and the Adjacent Metal Are Stronger than the Original Plate. Test Specimens Were Cut at 1-In. Intervals Parallel to the Weld and Pulled in the Same Direction.

before failure occurred. In this case, the full strength of the structure would be utilized and the stress at failure would equal the ultimate strength of the steel. It has been well established that ductility of a welded joint may be improved by a "stress-relieving treatment."

When extremely hot metal is deposited in the groove between plates to be joined, it has a localized effect on the steel, which, unless properly

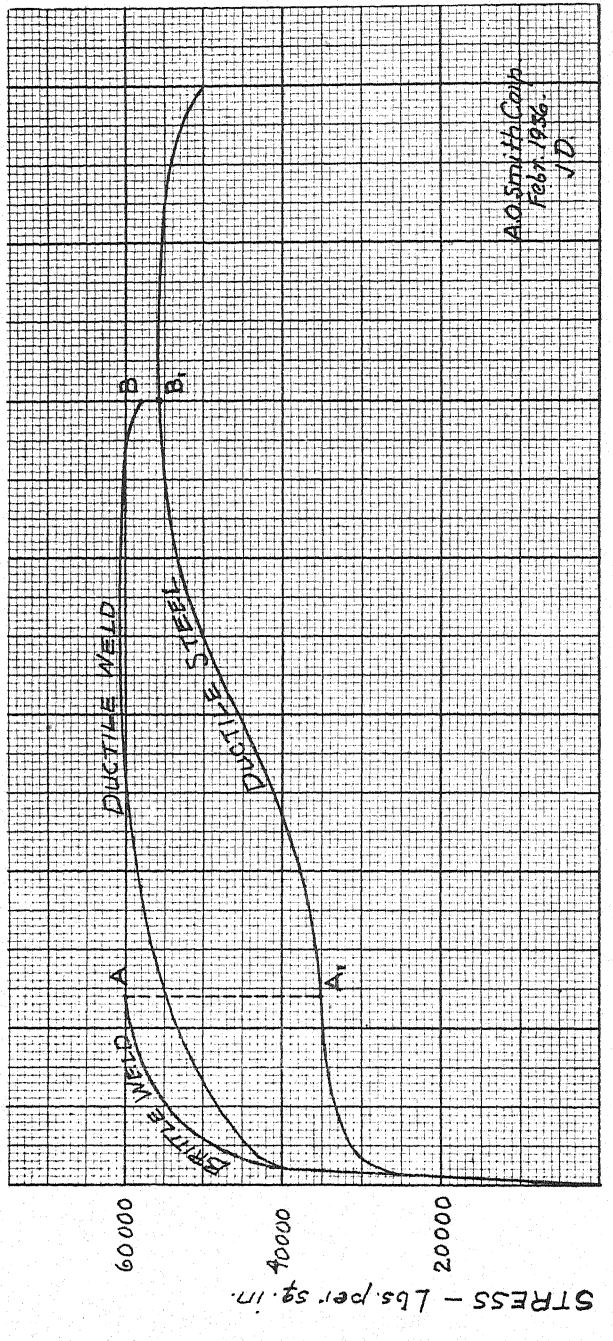


Fig. 2—Typical Stress-Strain Diagram for a Ductile Steel, a Ductile Weld and a Brittle Weld.

handled, will create undesirable conditions. Strains or stresses are developed by the shrinkage of succeeding layers as they are deposited and may accumulate to dangerous proportions in heavy welds, if they are not reduced or eliminated. There are three general methods for relieving such weld stresses: (1) by peening each layer as it is deposited, (2) by preheating the structure to be welded and performing the welding operation at temperatures above normal or (3) by appropriate heating of the finished structure (see chapter on Stress Relieving).

Non-Destructive Tests.—The development of industrial X-ray equipment presented an accurate and practical method which could be applied to the inspection of welded joints even in drums designed for the highest service requirements. Gamma ray may be used to advantage in place of the X-ray in certain cases. The magnetic powder test is useful for a number of special purposes. See Chapter 33B on Non-Destructive Testing of Welds.

Advantage of Fusion Welded Construction

The effect of welding in the pressure vessel industry was to reduce weight about 25% below that for a riveted drum, still maintaining the same safety. If the designer were reluctant to take advantage of the opportunity to re-

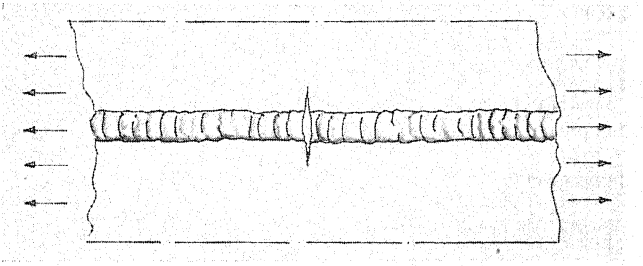


Fig. 3—Type of Failure that Is Likely to Occur with a Brittle Weld Joining a Ductile Steel When Stressed in a Direction Parallel to the Weld.

duce weight, the result obviously was that the structure as a whole had a greater fundamental factor of safety. The same principles of design improvement that welding was instrumental in developing for the pressure vessel industry, can be applied to advantage to nearly every type of engineering structure—for reduction of weight or increase of the fundamental safety factor. Modern structures, which have materially benefited from the application of welding in their design and manufacture, range from airplanes to locomotives, from bridges to boilers and from machinery parts to tanks and pipe, etc. Numerous other constructions owe their very existence to the fact that joints in steel can now be made, without overlapping, that are as strong, tough and ductile as the steel joined.

While there are limitations to fusion welded construction, they are associated fundamentally with the thermal effect of the welding heat in and adjacent to the welded joint and are, therefore, influenced by mass and material.

By a studied procedure control, it is possible to weld successfully some materials which might otherwise be considered unfit for fusion welding. It is also possible to design vessels to meet service requirements without calling for impractical plate thickness. Thus, development of a proper design and a satisfactory welding technique offered freedom from the inherent deficiencies of the riveted or forge welded joint and had an immediate effect on the boiler and pressure vessel industry, as well as on related industries in opening up a practically unlimited field of fabrication and application.

Advantages of Welded Construction.—The advantages of welded drum construction over the older methods of construction are as follows:

1. Higher joint efficiency as compared with riveted or forge welded construction.

In boiler drum construction where radiographic inspection and thermal stress relief are required without exception, the efficiency of the welded joint is set at 90%. In the construction of unfired pressure vessels, the weld joint efficiency is governed by various construction factors such as type of material used, type of welded joint, whether radiographed and/or stress-relieved, and the joint efficiency may be as high as 95%.

2. Elimination of caustic embrittlement to which riveted joints may be susceptible, and the elimination of the possibility of age hardening of cold-worked plate in riveted drums, by final thermal stress relief of a welded assembly.

3. Decrease in drum weight by reason of the greater joint efficiency and the elimination of butt straps and rivets.

4. Decrease in drum weight without affecting safety by using a design involving thinner shell sections at portions which are not weakened by tube holes or other unreinforced openings.

5. Elimination of highly stressed regions around rivet holes caused by the riveting operation.

6. Elimination of high stress concentration in service at regions where abrupt changes in section occur, by the more uniform contours obtainable with welded construction, as, for example, the use of a welded butt joint in place of a riveted lap joint for the attachment of heads to shell.

7. Elimination of the thickness limitations for riveted or forge welded drums, thus permitting high working pressures.

8. Extended choice of materials to utilize to advantage the high-temperature properties of special steels for service at elevated temperatures.

9. The economic advantage of welded construction from the standpoint of cost and production over forged seamless drum construction.

Some of the advantages enumerated above are obvious and immediately apparent. Others are more obscure and will require service experience over extended periods for practical demonstrations.

Adoption and Requirements of Codes and Specifications

The development of fusion welding as outlined above, and the excellent results obtained, led to the approval of fusion welding in various codes and specifications governing pressure vessel construction. In the fall of 1930, welded boiler drums were accepted by the Bureau of Engineering, U.S.N., and in 1931, rules for fusion welding were incorporated in the Boiler Construction Code of the American Society of Mechanical Engineers. In 1931, a joint A.P.I.-A.S.M.E. Committee on Unfired Pressure Vessels was appointed to prepare a code for the construction of unfired pressure vessels

for petroleum liquids and gases. At present, rules for fusion welding of boiler drums and pressure vessels have been adopted by the following:

1. Bureau of Engineering, U.S.N.
2. Boiler Code Committee, A.S.M.E.
3. Bureau of Marine Inspection and Navigation.
4. American Bureau of Shipping.
5. Lloyds Register of Shipping.
6. Joint A.P.I.-A.S.M.E. Committee for Unfired Pressure Vessels.
7. Inspection Boards of Various States.

Except for minor variations in production weld tests and welding operators' qualification tests, the requirements in all rules for fusion welding are essentially alike. All rules are identical in providing for:

1. Thermal stress relief of the completely welded vessel.
2. Radiographic examination of all main seams.
3. Representative test plates attached to and welded as a continuation of the longitudinal seams in shells.
4. Qualification tests for welding operators.

In the construction of boiler drums, there is no exception to the above requirements. In the construction of unfired pressure vessels, these requirements may be modified if the highest joint efficiency is not required, and thermal stress relief and/or radiographic examination may be eliminated. The tests and minimum results required for representative production welded test plates are given in Table 1. For detailed requirements on these and on welding operators' qualification test plates, reference should be made to individual codes.

The Effect of Welding on Design

Changes in Design Practice.—Before the advent of modern welding, joints could be made only by splicing or overlapping the plates, which usually were held together by means of bolts or rivets. The riveted joint whether lap or butt does not permit a uniform or smoothly graduated path for stress flow and introduces stress problems difficult to determine. Due to this inherent characteristic, the joint in a riveted vessel is the weakest part of the structure and justifies the custom of basing the safety factor on the strength of the longitudinal seam in the cylinder. This basis of design has become so firmly established with designing engineers, that they find it difficult to accept the full value of the welded joint and to take advantage of its properties to make improvements in design. By means of welding the designing engineer may take advantage of a uniform uninterrupted stress flow and design for butt-welded joints with weld metal as ductile, tough and strong as the material in the rest of the structure. In other words, the safety of the structure is no longer controlled by the joint, but by such factors as the shape of the heads, reinforcement of openings, proper distribution of metal, strength of ligaments between tube holes, etc. Yet, the tendency has largely been to substitute welding for riveting or bolting without consideration of its possibilities and significance. Designers would do well to readjust their methods of design procedure in order to reap the full benefits in increased safety or greater economy which are available to them.

Table 1—Requirements of Production Test Welds. Fusion Welded Pressure Vessels

	Bureau of Engineering, U. S. Navy	A.S.M.E. Boiler Code	Bureau of Marine Inspection and Navigation	A.P.I.-A.S.M.E.
Quality of test plate material	Taken from same plates as in drum construction	Taken from plates of same specification as that used in drum construction	Taken from plates of same specification as that used in drum construction	Taken from plates of same specification as that used in drum construction
Number of test plates required	One per drum	One per drum	Two per drum Test one	Over $1^1/_4$-in. plate, one per 100 ft. of weld Over $^1/_2$-in. plate, one per 200 ft. of weld Under $^1/_2$-in. plate, one per 300 ft. of weld
Transverse tension	None required	One required	One required	One required
Minimum tensile strength	.....	Minimum range of plate used	Minimum range of plate used	May be substituted for all-weld metal tensile
Free bend	Two guided bend tests	One required. 30% elongation across weld	One required. 30% elongation across weld	One free bend One reverse bend 30% elongation if stress-relieved 20% elongation if not stress-relieved
Nick-break test	None required	None required	None required	One required
All-weld tensile (0.505 in.)	One required	One required	One required	One required
Minimum tensile strength	Minimum range of plate	Minimum range of plate	Minimum range of plate	Minimum range of plate
Elongation in 2 in. minimum	25.0%	20.0%	20.0%	20.0%
				See Transverse Tension
Specific gravity	None required	None required	Two required Sp. gr. 7.80 minimum	None required

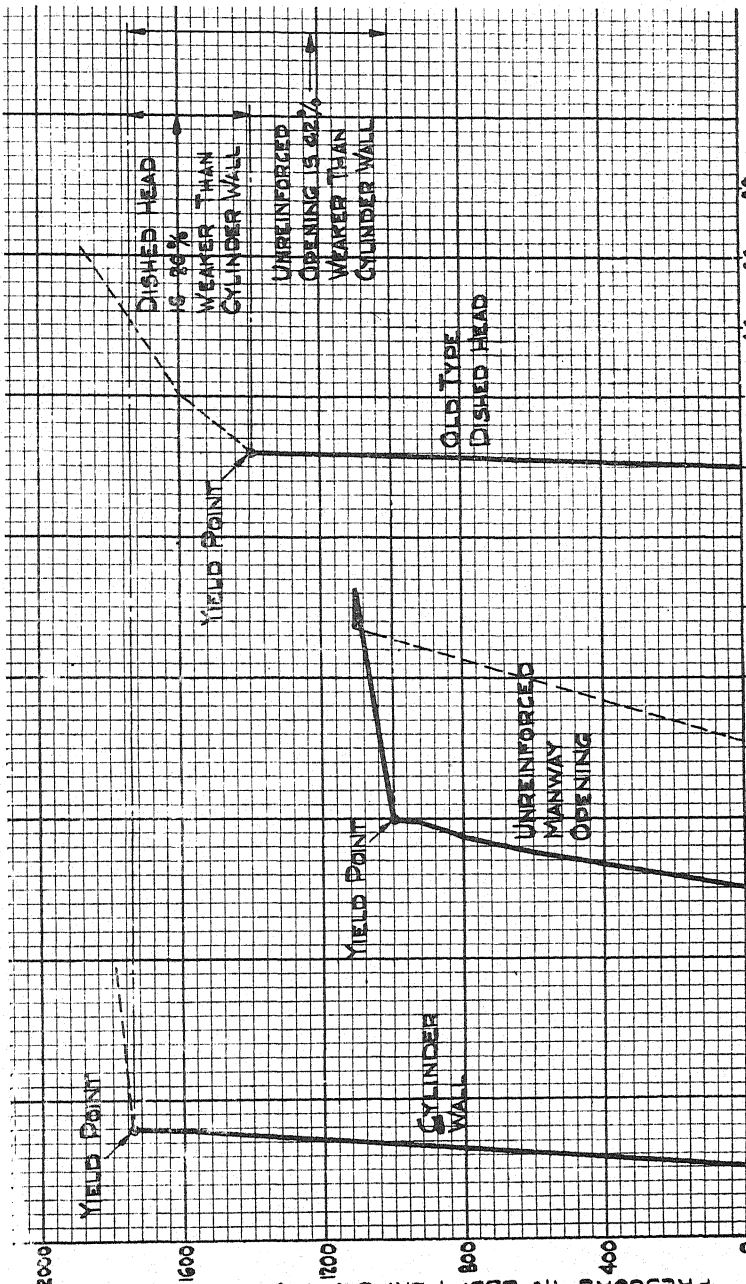


Fig. 4—Curves Showing Lack of Uniformity in the Strength of a Vessel with Dished Heads and Unreinforced Openings. These Test Results Were Obtained Simultaneously During One Pressure Test. The Metal at All Test Points Had the Same Yield Point.

Design of Welded Structures.—In the application of welding to designs, the aim should be to duplicate the safety that long experience and good engineering have indicated to be necessary in each case. The factors of safety used on many structures are factors applied to certain locations only. Often these locations were selected more for the ease with which stress calculations could be made in these places than because they were the locations of the highest stresses. That this situation was quite generally acknowledged is indicated by the frequent reference to the factor of safety as the "factor of ignorance," particularly in the pressure vessel field. Such a term need no longer be applicable, since welding has brought about the use of correct shapes and proper reinforcements. This results in vessels of more nearly uniform strength throughout and a dependable safety factor. Many other types of engineering structures gain similarly by the use of welding and the application of correct design principles.

Figure 4 shows three curves, representing the conditions of stress at as many critical points on a pressure vessel of the type of design which has prevailed for many years. It is well known that the factor of safety is based on the cylinder formula, but, as is seen, the cylinder is not the highest stressed element. Of the three points selected for the test, the unreinforced opening was the weakest. As a matter of fact, the safety factor based on the initial yield at the opening was only 3 while the official accepted factor was 5, based on the cylinder computation. Figure 5 shows corresponding curves when ellipsoidal heads and reinforced openings are used.

Tests such as those for which the results are shown in Figures 4 and 5 are useful in securing balanced designs. It should be borne in mind, however, that factors of safety based on the initial yield may not be a measure of the safety of a vessel when placed in service, as this is governed by the final distribution of the stresses under working conditions.

The knuckles of drum heads for the lower pressure ranges pass through the yield point under a hydrostatic test pressure of 200% of the working pressure. These drum heads, in general, perform satisfactorily for an indefinite period of time, even though the knuckle zone has been subjected to yield-point stresses. There is a definite reason for this satisfactory operation which ties in very closely with the relation between the test pressure and the yield point of the material. As the test pressure is applied, the yield point of the material is exceeded and some plastic distortion occurs, as evidenced by the appearance of Luders lines and cracking of the scale. When the hydrostatic pressure is released, these zones which have been subjected to plastic deformation return to a state of equilibrium in which compression stresses are established in the zones which have plastically deformed. Due to this change in the stress distribution in the plate, stresses are maintained at values well below the endurance limit under the normal operating pressure.

All codes and specifications covering the fabrication of drums for power boilers and for unfired pressure vessels under Paragraph U-68 of the A.S.-M.E. Code, permit an efficiency of 90% for the welded joints. The A.P.I.-A.S.M.E. Code covering unfired pressure vessels for petroleum liquids and gases provides factors which permit in the highest class of construction an efficiency of 95% for the welded joints. The factors of safety (ratio of the product of the ultimate tensile strength of the plate material and the

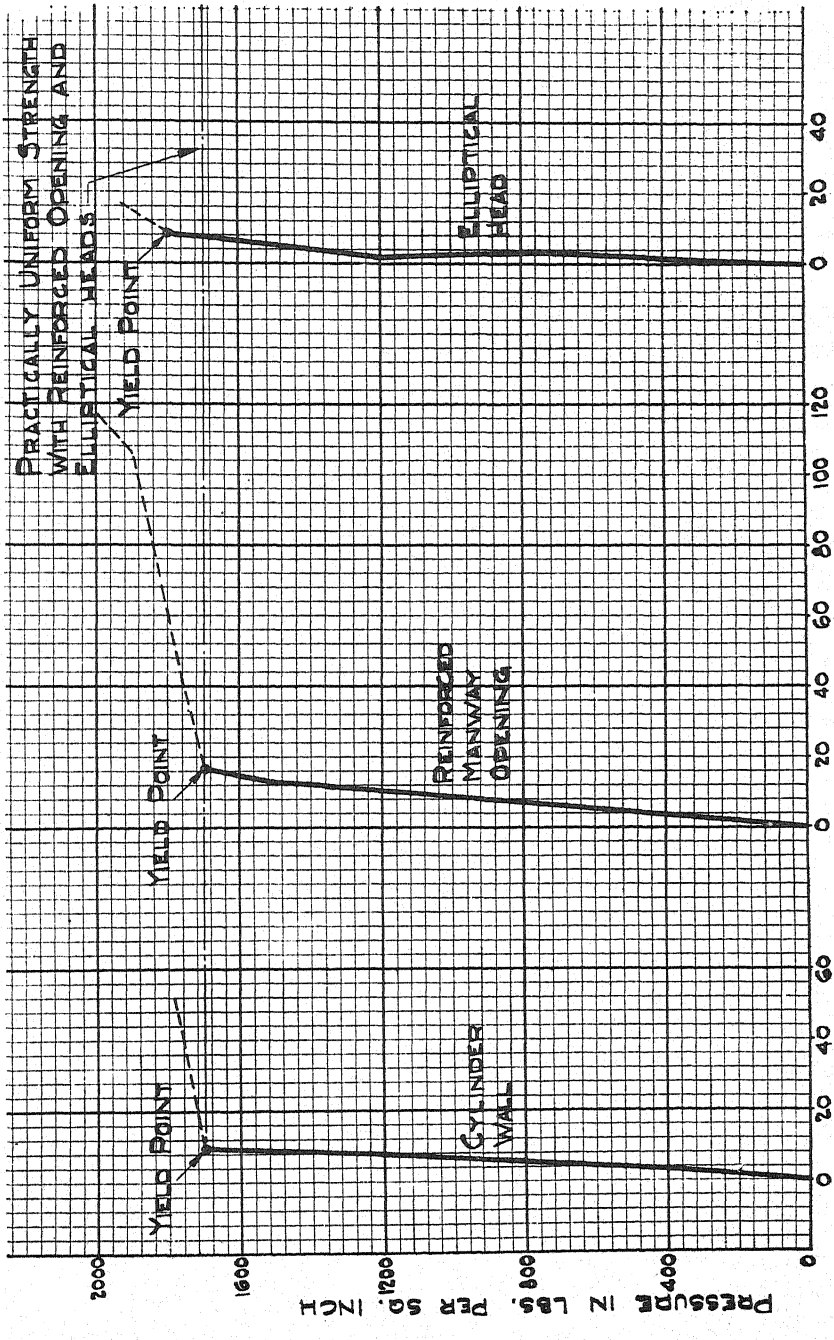


Fig. 5—Curves Showing Uniform Strength in a Vessel When Ellipsoidal Heads and Reinforced Openings Are Used.

Table 2—Showing the Comparisons Between the Factors of Safety and the Allowable Stress Across a Welded Joint in Pressure Vessels

	Ultimate Tensile Strength Plate Material (Minimum), Psi.	Joint Efficiency, %	Factor of Safety Allowed	Working Stress* Allowed, Psi. Across Weld Joint
Bureau of Engineering, U. S. Navy	60,000	100	4.0	15,000†
Bureau of Marine Inspection and Navigation	60,000	90	4.5	12,000
A.S.M.E. Boiler Code	55,000	90	5.0	9,900
A.S.M.E. Boiler Code	65,000	90	5.0	11,700
A.S.M.E. Boiler Code	70,000	90	5.0	12,600
A.P.I.-A.S.M.E. Code	55,000	95‡	4.0	13,060
A.P.I.-A.S.M.E. Code	70,000	95‡	4.0	16,625

* Allowable working stress $= \frac{\text{tensile strength of plate}}{\text{factor of safety}} \times$ weld joint efficiency.

† This figure is not directly comparable with the others as it includes the stress due to the permissible out-of-roundness which is not included in the others.

‡ For highest class of construction. Radiographed and stress-relieved.

Note: With plate material of higher ultimate tensile strength a corresponding increase in working stress across the weld joint is permitted.

weld joint efficiency to the allowable working stress for that material) vary for the individual codes and specifications with resultant allowable design working stresses for welded construction as shown in Table 2.

There is a special rule in the A.S.M.E. Unfired Pressure Vessel Code for seamless forged vessels in which the effect of stress raises is minimized, which sanctions a factor of safety of 4 in place of 5 for certain grades of high-tensile strength steel for low-temperature service. The rule prohibits the placing of holes in the thinner part of the shell which has a thickness corresponding to a factor of safety of 4. It contains a requirement that when a reinforced opening is placed in a shell it shall be made of a uniform thickness for its entire circumference where reinforced, the thickness being such that the calculated stress in the reinforced part before piercing for the opening is not more than one-half the maximum stress allowed for the thinner part of the shell. The end of the reinforced part is tapered to avoid stress concentration where it meets the thinner part of the shell. These values apply only when the working temperature does not exceed approximately 650°F. At higher operating temperatures, the high-temperature properties of the materials of construction must be considered resulting in a progressive reduction in the allowable working stress. The values prescribed in the A.S.M.E. Power Boiler Code are given in Table 3.

A number of different types of constructions are involved in the design of welded drum shells, i.e., the straight cylindrical portion of the drums between heads. Figure 6-A shows a shell of uniform thickness rolled from a single plate and the edges joined by a single longitudinal butt weld. Limitations in available plate sizes and capacity of forming rolls restrict this construction to relatively small low pressure single-plate drums or to those long vessels in which a number of courses made up of such rings are joined by circumferential seams.

Table 3—Maximum Allowable Working Stresses for Ferrous Materials in Pounds per Square Inch

Specification number	Grade	Spec., minimum tensile	Notes and limitations	For metal temperatures not exceeding deg F: −20 to 650	700	750	800	850	900	950	1000	1050	1100	1150	1200
PLATE STEELS															
Carbon Steel															
S-1		55000	(1)	11000	10400	9500	8000	6300	4400	2600	...	..	..	..	..
S-2	A	45000	(1)	9000	8800	8400	6900	5700	4400	2600	...	..	..	..	..
S-2	B	50000	(1)	10000	9600	9000	7500	6000	4400	2600	...	..	..	..	..
S-42	A	55000		11000	10400	9500	8500	7200	5600	3800	2000	..	..	..	..
S-42	B	60000		12000	11400	10400	9100	7400	5600	3800	2000	..	..	..	..
S-55	A	65000		13000	12300	11100	9400	7600	5600	3800	2000	..	..	..	..
S-55	B	70000		14000	13300	11900	10000	7800	5600	3800	2000	..	..	..	..
Low-Alloy Steels															
S-28	A	75000		15000	14100	12400	10100	7800	5600	3800	2000	..	..	..	..
S-28	B	85000		15000	14100	12400	10100	7800	5600	3800	2000	..	..	..	..
S-43	A	65000		13000	12300	11100	9400	7600	5600	3800	2000	..	..	..	..
S-43	B	70000		14000	13300	11900	10000	7800	5600	3800	2000	..	..	..	..
S-43	C	75000		15000	14100	12400	10100	7800	5600	3800	2000	..	..	..	..
S-44	A	65000		13000	13000	13000	12500	11500	10000	8000	5000	..	..	..	..
S-44	B	70000		14000	14000	14000	13500	12000	10200	8000	5000	..	..	..	..
S-44	C	75000		15000	15000	15000	14400	12700	10400	8000	5000	..	..	..	..
S-60	A	70000	(13)	14000	14000	14000	...	...	...	...	...	..	..	..	..
S-60	B	75000	(13)	15000	15000	15000	...	...	...	...	...	..	..	..	..
Medium and High Alloy Steels															
A.S.T.M. A176-39*...	1	70000		14000	14000	14000	12800	9500	6750	4000	2400	..	..	..	..
A.S.T.M. A176-39*...	2	70000		14000	14000	14000	12800	9500	6750	4000	2400	..	..	..	..
A.S.T.M. A167-39*...	304, 308	75000	(2)	15000	15000	14600	14300	14000	13400	12300	10000	8000	6000	4600	3600
A.S.T.M. A167-39*...	316, 317	75000	(2)	15000	15000	14600	14300	14000	13400	12600	11200	9000	7000	5000	3600
A.S.T.M. A167-39*...	321	75000		15000	15000	14600	14300	14000	13400	12300	10000	8000	6000	4600	3600
A.S.T.M. A167-39*...	347	75000		15000	15000	14600	14300	14000	13400	12300	10000	8000	6000	4600	3600

NOTES:

(1) Flange quality not permitted above 850 F.

(2) No allowance has been made for corrosive action in the allowable stresses given. Carbide precipitation in service is also to be expected at temperatures above 750 F.

(13) Between temperatures of 750 to 1000 F, the stresses given herein for killed carbon steel, Specification S-55, Grade B, may be used until high temperature test data become available.

GENERAL:

Carbon steel materials covered by Boiler Code specifications which are not included in these tables are limited to use at temperatures of from −20 to 650 F.

The allowable stress in wrought materials is one-fifth of the ultimate; in cast materials, it is one-fifth of the ultimate multiplied by the applicable quality factor for design purposes.

* While these specifications have not been approved by the Boiler Code Committee for incorporation in the Code, the stresses given herein have been included to cover foreseen requests for such data.

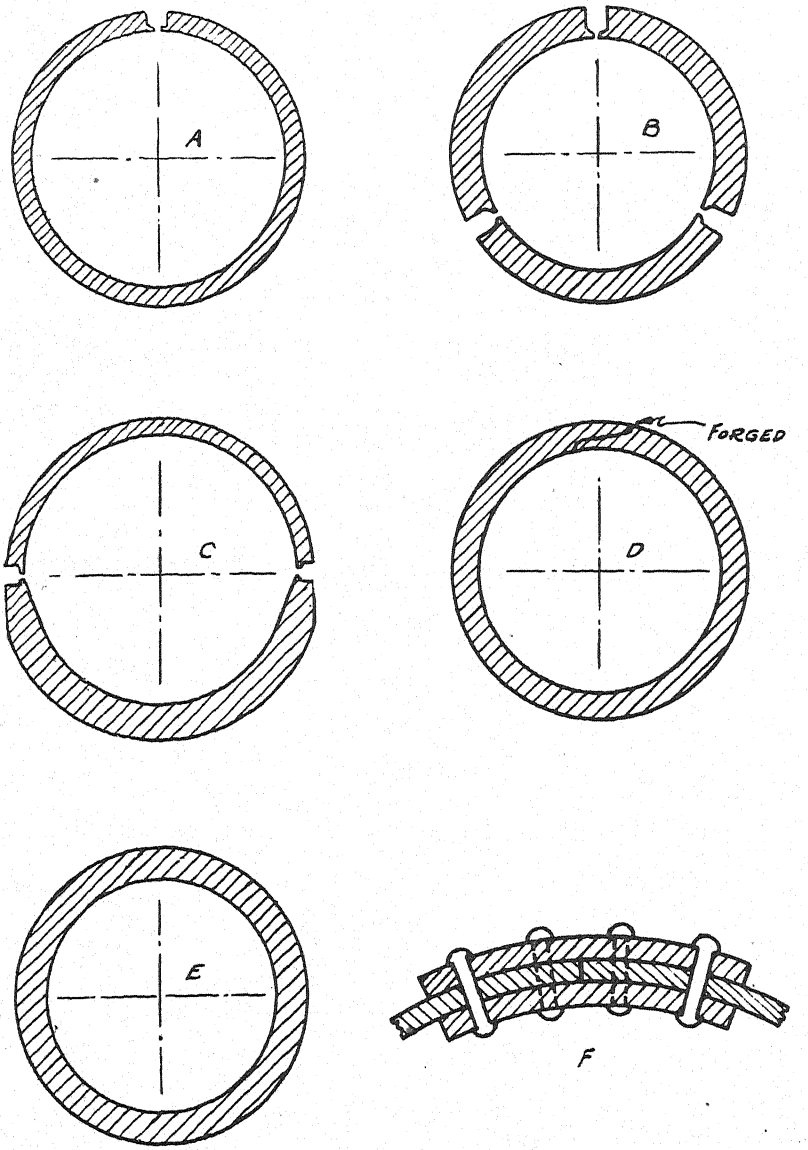


Fig. 6—Types of Shell Joints

(A) Shell of uniform thickness rolled from a single plate. One longitudinal seam.

(B) Heavy shell of uniform thickness. Two or more shell elements. Two or more longitudinal seams.

(C) Tube and wrapper plate construction. Two or more longitudinal seams.

(D) Forge and hammer weld construction. Limiting thickness approximately 2 in. maximum. Low strength plate.

(E) Forged seamless drum.

(F) Butt and double strap riveted joint. Limiting thickness approximately $2^1/_2$ in. maximum.

In Fig. 6-B, a heavy shell of uniform thickness is made up of two or more plates forming longitudinal elements joined by two or more longitudinal welds. Such construction is necessary in heavy shells when all plates are weakened by tube holes or other unreinforced openings when size and/or fabricating limitations do not permit single-plate construction. Again for the larger drums, this construction is often more economical than that shown in Fig. 6-A by reason of the lower per pound cost of narrower plates in comparison with that of a single extremely wide plate. In very large drums, such construction may be a necessity by size limitations of available plates.

Multiple plate shells may be of non-uniform thickness as in Fig. 6-C which shows thicker plate for that shell element which is weakened by tube holes, e.g., the tube sheet in boiler drums. The balance of the shell, i.e., the wrapper sheet, may be relatively thinner since it is not weakened by a large number of openings.

This construction, particularly valuable for boiler drums, affords a considerable saving in drum weight without any structural disadvantage. It illustrates one important advantage of fusion welded construction, that of obtaining symmetrical butt joints from thick to thin sections without sacrificing a uniform transmission of stress.

Figure 6-D illustrates a typical forge and hammer welded shell construction in which the overlapped edges of a single rolled plate have been forge welded. This construction is limited to low strength plate of 2-in. maximum thickness so that it is unable to cope with demands of high-pressure operation.

Figure 6-E representing forged seamless construction is typical of what was once considered the ideal design, although it is limited in size by equipment available and in weight by ingot capacity, approximately 60,000 to 70,000 lb.

Other constructions of shell segments joined by circumferential and longitudinal welds, may be used in addition to the above more generally used designs. In boiler drum construction of practically all the above designs, the minimum plate thickness is governed by the longitudinal tube ligament efficiency, which is generally much lower than the 90% allowable efficiency of the weld. Figure 6-C is an exception in this respect as here the 90% joint efficiency may determine the thickness of the weld and wrapper plate. In other classes of pressure vessels, the welded joint efficiency governs provided all openings are properly designed and reinforced.

Where thick and thin shell sections, Fig. 6-C, are joined by butt welds, the thick section is reduced by machining a uniform taper to the thickness of the thinner section. In this way, the circle of both sections is coincident and avoids the indeterminate stress concentrations of an unsymmetrical system. Greater significance could be placed in this feature and on the use of tapered reinforcements in design for equal safety at higher allowable stresses. This is particularly significant in the trend toward higher strength carbon and alloy steels as pressure vessel materials.

It is readily apparent by comparison with Fig. 6-F, that the design of the welded joint is intrinsically more sound than the riveted joint from the standpoint of uniform stress distribution and that many of the structural

limitations which attend other methods are largely eliminated by the use of welded joints.

Heads.—Figures 7-A, 7-B and 7-C illustrate typical welded joints between shells and heads. The flanges of both blank heads and heads containing manholes may be of different thickness from that of the shell to which they are attached. If of different thickness, the head or the shell is machined to give the same thickness. Machining of the ends of the shell is necessary in all cases to produce a uniform thickness at the joint, Fig. 7-C.

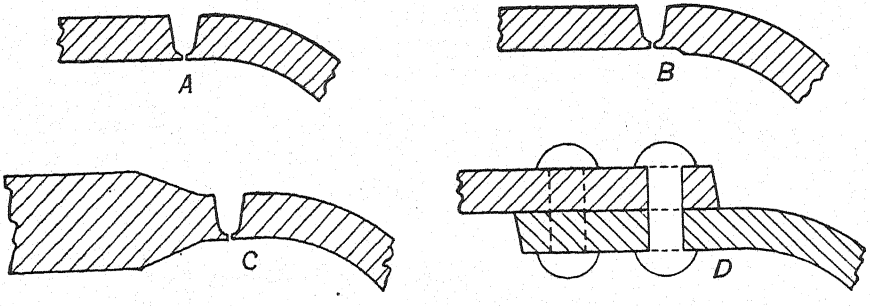


Fig. 7—Types of Head Joints

(A) Shell and head of uniform thickness.
(B) Heavy head machined to thickness of shell.
(C) Heavy tube sheet machined to thickness of head.
(D) Lap-riveted head seam.

Nozzle Attachment to Shell.—Various methods are used for the attachment of nozzles and other pressure part connections. Acceptable types of design are shown in Figs. 8 and 9 reproduced from Figs. P-36 and P-38 of the A.S.M.E. Boiler Construction Code. Figure 9 illustrates a type of nozzle provided with a welding flange which may be inserted in an opening in the shell and butt welded. Radiographic examination of this type of weld is readily performed.

Proof Testing to Improve Designs.—Proving of designs is a question which most designing engineers could well afford to consider. It is not always necessary to test structures to failure to gain the objective, nor is it even necessary to test them to the point where their value or future usefulness has been impaired. Before good welding was available, however, designs could not be easily proved.

A non-destructive test method which has proved very useful in checking design, consists of covering the parts to be studied with lime wash, which will flake off at the weakest points first when the load is applied. In one case a dished head was thus tested as part of a vessel. The wall thickness was uniform throughout this vessel and, knowing the actual strength of the steel, it was possible to calculate the stresses in the cylindrical portion quite accurately. Under pressure stress lines were brought out by the flaking of the lime wash near the knuckle radius of the head. The steel first started to yield in that area and it occurred at a stress which was only 80% of the known yield strength of the cylinder.

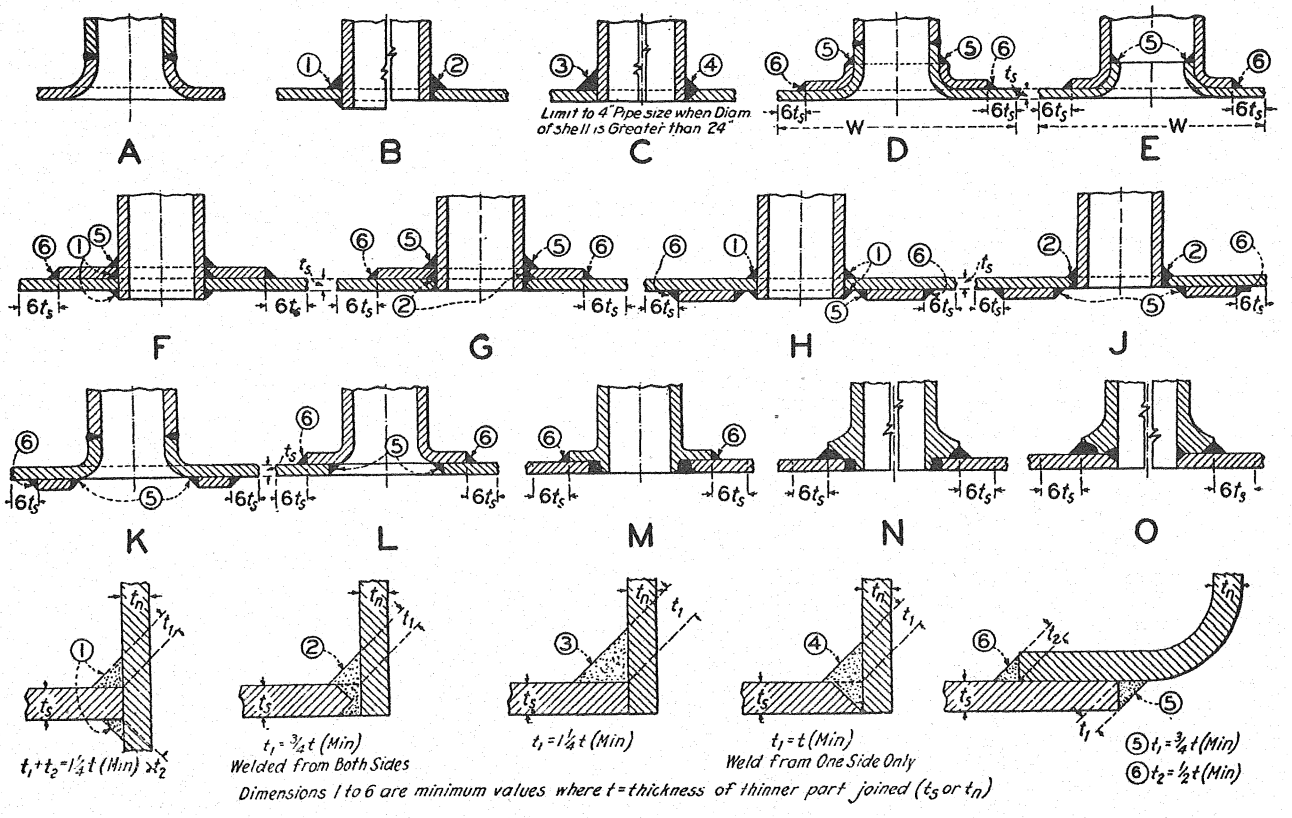


Fig. 8—Some Acceptable Types of Fusion Welded Nozzle Construction

The results when the same test was made on an all ellipsoidal head (2 to 1 ratio) attached to the same vessel as the dished head showed no area of stress intensification. They indicate that this type of ellipsoidal head permits a more balanced design inasmuch as equal thickness of heads and cylinder would result in a more nearly uniform stress condition. Subsequent tests to destruction on both types of heads very clearly demonstrated the superiority of the ellipsoidal head, since vessels equipped with such heads invariably did not fail until the full strength of the steel was reached.

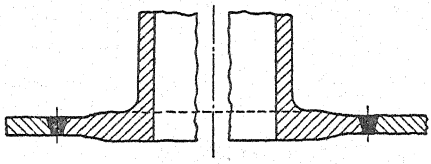


Fig. 9—Inserted Type Nozzles

The vessel with the conventional dished head eventually failed in that head at about 80% of the cylinder strength as established by tensile tests on the steel used.

As a check on the above test, strain-gage measurements were also taken on the same vessels, with the results given in Figs. 4 and 5. Although this method gives numerical values, the points of maximum stress are hard to locate, the method is tedious and unless carefully analyzed, may give misleading results. It is less expensive and much easier to cover the whole structure with lime wash and look for the flaking when it is subjected to hydrostatic pressure.

The lime wash method can be applied with equal success to nearly every type of welded structure. Flaking of the lime will reveal any localized area that may be inadequately designed, thus enabling the designer to remedy the weakness by proper change of shape or reinforcement at that point. There are other superior brittle coatings such as the one sold under the trade name "Stress-Coat." These will also assist him in better balancing future designs, resulting in material savings and lasting value at the nominal expense of a few tests.

The strain-gage method has been used in testing scale models in lieu of the full-sized structure. This method requires a careful analysis and interpretation of results because the action under load is very often quite different from that of the same design in smaller scale. More and more attention will undoubtedly be paid to designing fusion welded vessels so as to use the material from which they are constructed in the most economical way. As already stated, the Boiler Code Committee has specified tapered reinforcements and other means of reducing the effect of stress raisers for certain special constructions and allowed higher working pressures for such constructions than where there are no stress raisers. There is a broad field open for improvement which, if properly carried out, should result in the use of higher allowable working stresses than at present. Before sanctioning the use of higher working stresses, however, the possibility of corrosion fatigue and of the so-called aging of the steel must be considered. More

and more data are being secured on the use of special alloy steels and their behavior under different working conditions, and in view of their increased cost a reduction in weight would be especially advantageous. There is a vast field to consider in making advances, and due caution must be taken to avoid unforeseen difficulties.

A correct design would be secured by proportioning the tube holes and any other unreinforced openings so as to meet conditions which have been found to be safe through long-established practice or through intermittent pressure tests. By employing 2-in. strain gages in determining stresses in individual localities in the way that was done at Boulder Dam many of the abrupt section changes that are now allowed would not be permissible and the structures as a whole could be made to weigh less and cost less and be as safe as they are today. The field is open for advancement and important improvements are bound to be developed.

Materials Used in Construction

One of the important advantages which followed the development of welding is the wider choice of materials thus made available for pressure vessel construction. Less direct is the effect on the production of quality teels. It had often been demonstrated in earlier days of welded construction that the quality of the steel could be an important factor in the results obtained in welding. Through the generous cooperation of the steel producer, plate quality has been improved until early troubles which could be attributed to plate quality have largely been eliminated.

Fortunately for the early advocates of welding, boiler drums and pressure vessels were then operated under such conditions that satisfactory and economical constructions were obtained with plain carbon steels of relatively low tensile strength. For example, drum plate material was confined to ordinary flange and firebox steel of 55,000 or 60,000 psi. minimum tensile strength. This type of steel, for many years the standard material for riveted construction, was suitable for fusion welding. This same general class of material was used for other component parts of pressure vessels and auxiliary equipment such as headers, piping, boiler tubes and superheater and economizer tubular elements. Since then the situation has changed tremendously, not only by the introduction of alloy steels having special properties, but also by the introduction of new methods of fabrication. These changes in material and construction of boiler drums and pressure vessels have been necessitated by the application of increasingly higher operating pressures and temperatures in power plant and industrial process equipment.

Present-day operating extremes include: boiler operations at 2600 psi. pressure; superheated steam temperatures of 900 to 950°F.; process vessels operating at 950 to 975°F. and at the other extreme of the temperature range as low as −40 to −150°F. Each set of operating conditions introduces specific requirements which must be considered in the selection of a suitable material for fabrication. Higher operating pressures for a vessel of given diameter involve either an increase in wall thickness or the use of steel of higher strength than normal plain carbon steel to permit higher

allowable working stresses. At temperatures in excess of approximately 650 to 700°F., plain carbon steel suffers a loss in tensile strength and for such service, a special steel is required which by the addition of alloying elements will possess greater strength at high temperature and thus permit the use of higher working stresses. In the low-temperature range of operation, i.e., at temperatures lower than normal, the properties of steel must again be examined with particular reference to notch toughness or resistance to failure by impact.

The low carbon flange or firebox steel, due to the inadequate physical properties at high or very low temperatures (Fig. 10), is entirely unsatisfactory under conditions imposed by the above requirements or is uneconomical for high-pressure service due to the increased thickness required. New steels to meet the more severe service requirements have been developed by changing the chemistry of the steel plate in order to improve the physical properties in line with service requirements. While an increase in carbon content may suffice to raise the tensile strength of steel and satisfy requirements as to strength for service up to 650°F., this element is, in general, held to a maximum of 0.35% for steel which is to be welded. For service at temperatures above 650°F. and below 0°F., special properties are required. Steels possessing these properties are obtained by the addition of alloying elements from a few tenths of 1% upward. Carbon, which strictly speaking, cannot be considered as an alloying element, increases the tensile strength and hardness and reduces the ductility of the steel. Other elements such as manganese, chromium, molybdenum, vanadium, tungsten, nickel and silicon exert a similar influence, but to a lesser degree. Nickel and silicon are the least effective in this respect in low carbon steel.

Fundamentally, the important factor in the design of a pressure vessel is the working pressure. The working pressure, translated into stress, controls the thickness and class of material used in fabrication, based on fixed allowable working stresses for different materials at specified temperatures of operation. The allowable working stress is a function of the tensile strength, and the relation between them taking joint efficiency into account represents the factor of safety. This relationship between the short-time tensile strength and the allowable working stress through a range of temperature, of a 0.20% carbon steel having a minimum room temperature strength of 60,000 psi., is shown in Fig. 11. For carbon steels, the allowable working stress remains constant up to 650°F. and then drops rapidly due to the decreased strength exhibited at higher temperatures. In the range above 650°F., the ratio of tensile strength over allowable working stress increases with rising temperature, due to the introduction of creep or slow plastic deformation at elevated temperatures.

In contrast to the low allowable working stress of carbon steels in the 55,000 to 65,000 tensile range, we find that by (1) an increase in carbon content or by (2) the addition of suitable alloying elements, we may by virtue of the improved properties of the steel increase the allowable working stress in the first case at temperatures below, and in the second case at temperatures above 650°F., Fig. 12. It naturally follows, therefore, that the plate thickness required for a given working pressure and temperature may be materially reduced with attendant economy in fabrication.

When steel is subjected to certain conditions of stress and temperature

for extended periods of time, slow plastic deformation or creep occurs. Creep strength is usually designated as the stress at any given temperature which will produce a specified low deformation rate—1% in 10,000 hr. or 1% in 100,000 hr. (Figs. 13 and 14).

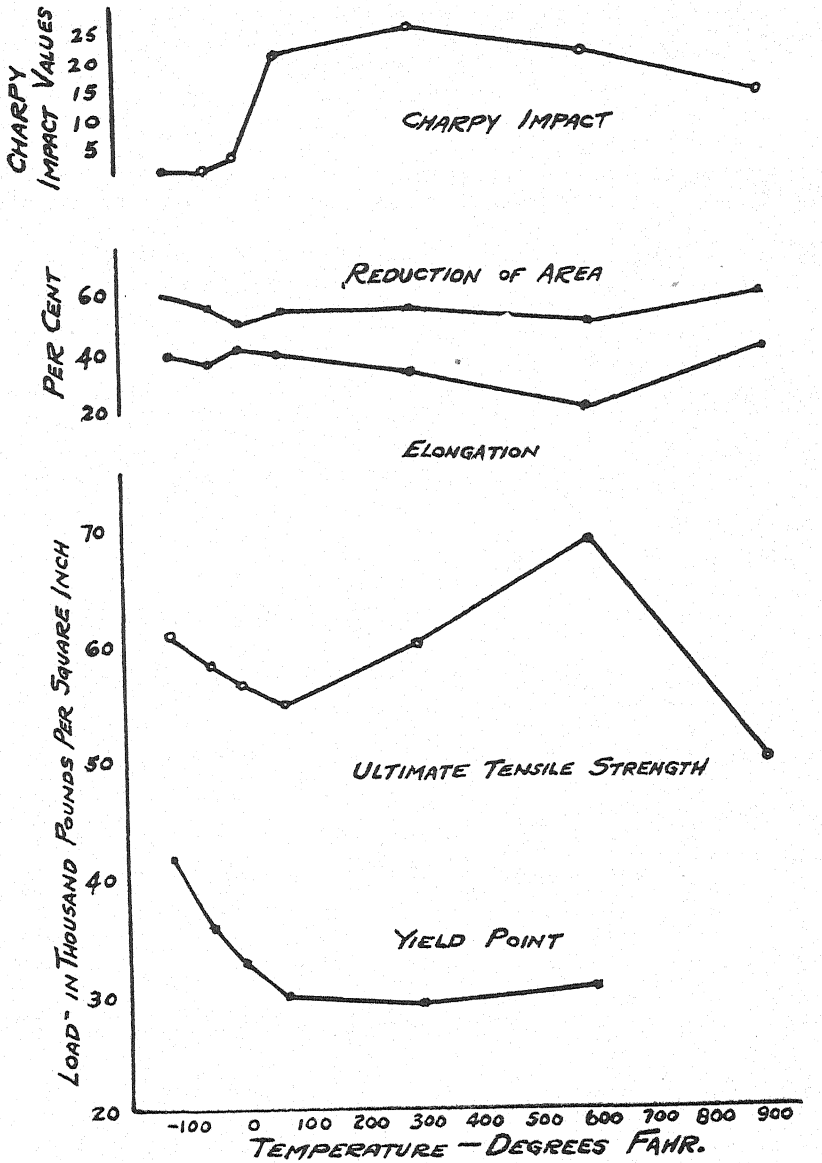


Fig. 10—Physical Properties of Boiler Plate at Various Temperatures

At elevated temperatures, carbon steel exhibits a high rate of creep at relatively low stress. For this type of service an alloy steel is required which possesses appropriate high-temperature properties. While certain low alloy steels will possess greatly improved strength over carbon steel, at temperatures above 650°F., they are limited to a maximum service temperature of approximately 975°F., since their oxidation resistance is the same or only slightly superior to that of plain carbon steel. For service at temperatures in excess of approximately 975 to 1000°F., steel must possess, in addition to high-temperature strength, increased resistance to attack by high-temperature air or furnace gases.

There have been pointed out factors of economy and suitability which influence the selection of a steel for a given service. Another very important factor in the construction of pressure vessels is the choice of steel which may be successfully welded. Welding is today and will continue to be inseparably associated with pressure vessel construction and has become the most favored and in many cases the necessary method of fabrication. Although today, with the correct type of filler metal and welding technique, nearly all commercial steels used in quantity can be welded with assurance that the joints will have physical properties equivalent to those of the plate material, the various codes have restricted the choice of steels which

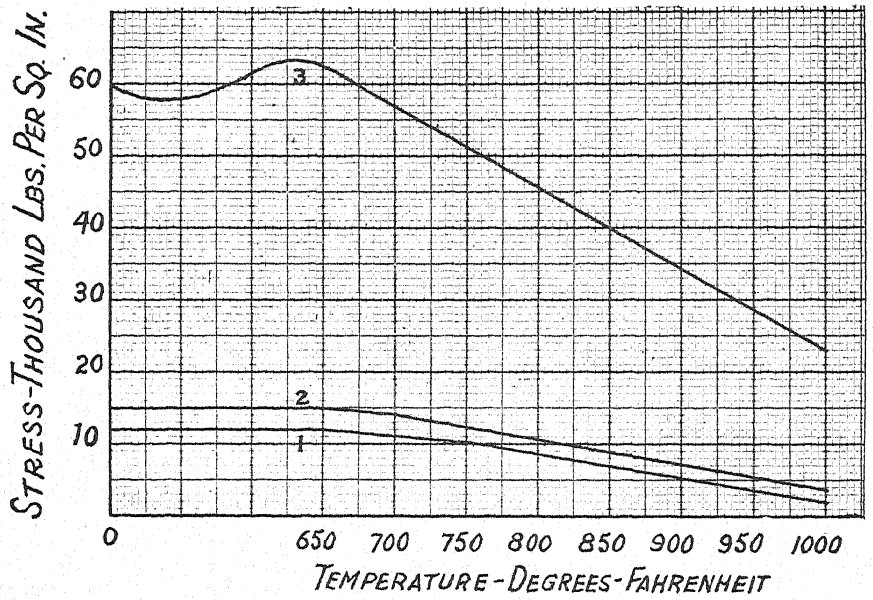


Fig. 11—Relation Between the Short-Time Tensile Strength and the Allowable Working Stress of 0.20% Carbon Steel. Allowable Working Stress Based on Plate of 60,000 Minimum Tensile Strength

1. Allowable working stress, A.S.M.E. Code. Safety factor 5.
2. Allowable working stress A.P.I.-A.S.M.E. Code. Safety factor 4.
3. Short-time tensile strength.

may be used in the construction of welded pressure vessels to a number of approved steel specifications.

Materials Used for Boiler Drum Construction.—The various codes regulating the construction by welding of drums for power boilers have approved the steels listed in Table 4 for this purpose.

Items 1, 2 and 6 are steels, usually of the open rimming or semi-killed type, which have for a long time been used in riveted construction for stationary and marine boilers. The steels contain an average of approximately 0.20 to 0.26% carbon and are readily welded without special precaution provided a suitable welding practice is used.

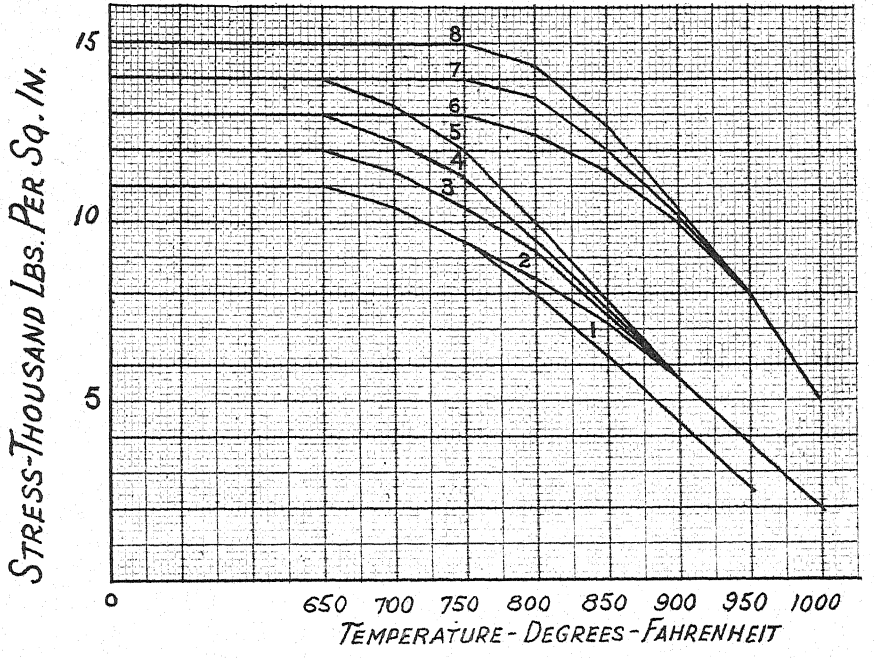


Fig. 12—Maximum Allowable Working Stress for Plate Material at Various Temperatures. A.S.M.E. Code

1. S-1 (A.S.T.M. A-70) rimmed steel 55,000 min. T.S.
2. S-42A (A.S.T.M. A-201) C-Si steel 55,000 min. T.S.
3. S-42B (A.S.T.M. A-201) C-Si steel 60,000 min. T.S.
4. S-55A (A.S.T.M. A-212) C-Si steel 65,000 min. T.S.
   S-43A (A.S.T.M. A-203) C-Ni steel 65,000 min. T.S.
5. S-55B (A.S.T.M. A-212) C-Si steel 70,000 min. T.S.
   S-43B (A.S.T.M. A-203) C-Ni steel 70,000 min. T.S.
6. S-44A (A.S.T.M. A-204) 0.50% Mo steel 65,000 min. T.S.
7. S-44B (A.S.T.M. A-204) 0.50% Mo steel 70,000 min. T.S.
8. S-44C (A.S.T.M. A-204) 0.50% Mo steel 75,000 min. T.S.

Safety factor 5 applies to 650°F. on steels 1, 2, 3, 4 and 5. Safety factor 5 applies to 750°F. on steels 6, 7 and 8.

Allowable working stress of material × joint efficiency = allowable working stress across welded joint.

Item 3 covers a recently approved carbon steel which may be used for boiler drums up to 6 in. in thickness. The carbon content of this steel has been graded upward with increasing plate thickness in order to maintain the tensile requirements. The tensile properties for a given carbon content have been improved by the addition of silicon, and the deoxidizing effect of that element has been utilized to produce a steel of higher quality, particularly important in very thick plates.

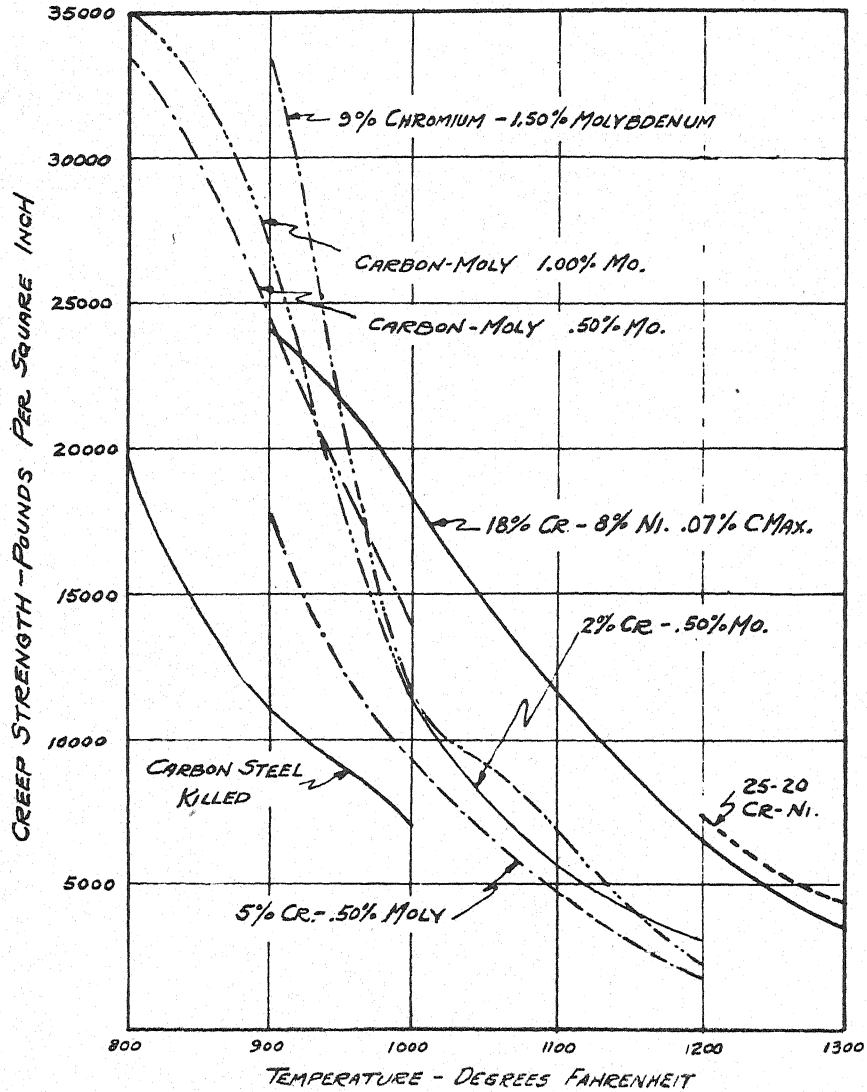


Fig. 13—Curves Showing Comparative Creep Strength of Various Steels — Rate = 1% in 10,000 Hr.

Item 4 covers a high-tensile strength carbon steel plate primarily adapted to high-pressure boiler drums. The higher strength of this steel up to 650°F. permits a corresponding increase in the allowable working stress and thinner plate may be used for a given pressure, with a saving of approximately 20 to 25% in weight.

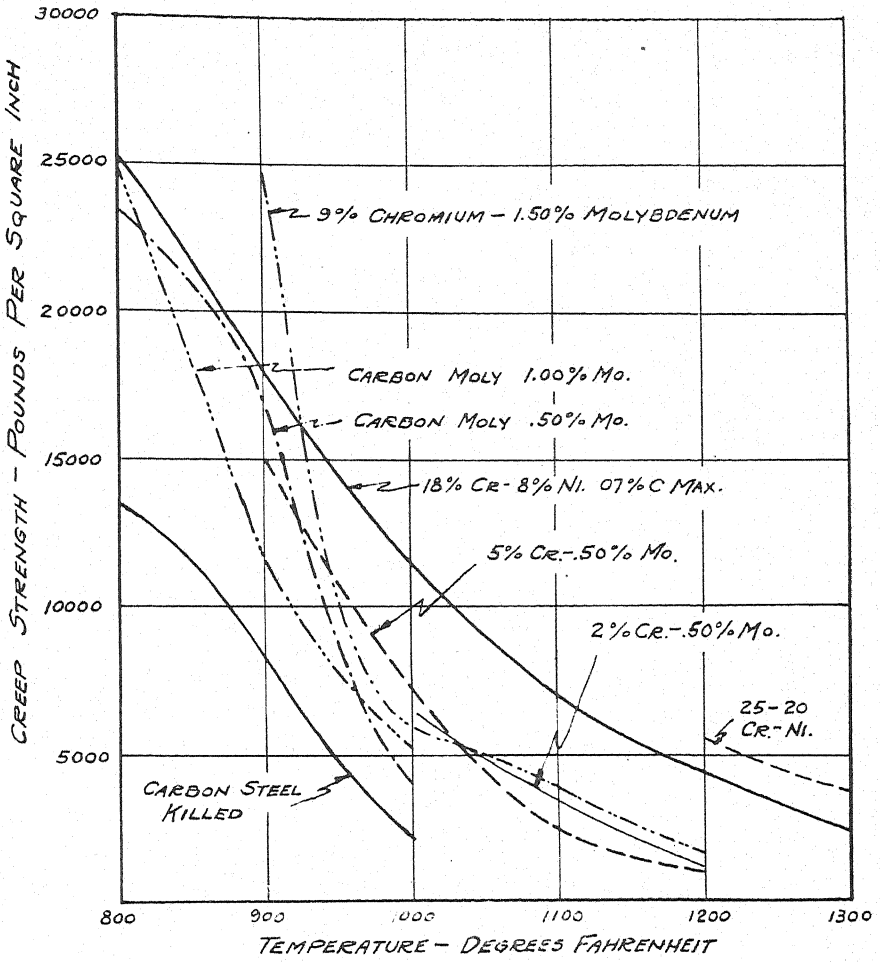


Fig. 14—Curves Showing Comparative Creep Strength of Various Steels—Rate = 1% in 100,000 Hr.

This type of steel is being used in a large proportion of the boiler drums fabricated today. The carbon content approaches what is considered the safe maximum for welded construction—0.35%, and the manganese content is higher than in the lower tensile grades. Since the hardening effect of both of these elements is quite pronounced, this steel requires greater precaution in welding than the lower tensile strength steel.

Table 4—Principal Materials Used in Pressure Vessel Construction (Standard Specifications with Summary of Tensile and Chemical Requirements)

Plate Specifications	Tensile Range, Psi.	Chemical Analysis C	Mn	S (3)	P (3)	Si	Other Elements
1. Carbon steel plates for boilers and pressure vessels. A.S.T.M. A70–39 (A.S.M.E. Boiler Code S-1)	55–65,000	0.25 (1) 0.30 (2)	0.80 max.	0.04 max.	0.035 max.	...	...
2. Marine boiler steel plate. (Bureau of Marine Inspection and Navigation—Rule 1, Sec. M2)	Grade A 60–70,000	(4)	0.90 max.	0.04 max.	0.035 max.	0.25 max.	...
	Grade B 55–65,000	(4)	0.90 max.	0.04 max.	0.035 max.	0.25 max.	...
3. Carbon-silicon-steel plate of ordinary tensile ranges for fusion welded boilers and other pressure vessels. A.S.T.M. A201–39 (A.S.M.E. S-42)	Grade A 55–65,000	0.20 0.24 0.27 0.31 (5)	0.80 max.	0.04 max.	0.035 max.	0.15–0.30	...
	Grade B 60–70,000	0.24 0.27 0.30 0.35 (5)	0.80 max.	0.04 max.	0.035 max.	0.15–0.30	...
4. High-tensile carbon-silicon-steel plates for boilers and other pressure vessels. Plates $4\frac{1}{2}$ in. and under in thickness. A.S.T.M. A212–39 (A.S.M.E. S-55)	Grade A 65–77,000	0.28 0.31 0.33 (6)	0.90 max.	0.04 max.	0.035 max.	0.15–0.30	...
	Grade B 70–82,000	0.31 0.33 0.35 (6)	0.90 max.	0.04 max.	0.035 max.	0.15–0.30	...
5. Molybdenum-steel plates for boilers and other pressure vessels. A.S.T.M. A204–39 (A.S.M.E. S-44). Grades A and B to 6 in., inclusive, in thickness. Grade C to 4 in., inclusive, in thickness	Grade A 65–77,000	0.18 0.21 0.23 (7)	0.50–0.90	0.04	0.035	0.15–0.30	0.40–0.60 Mo
	Grade B 70–82,000	0.25 0.20 0.23 0.25 (7)	0.50–0.90	0.04	0.035	0.15–0.30	0.40–0.60 Mo
	Grade C 75–87,000	0.27 0.23 0.26 (7) 0.28	0.50–0.90	0.04	0.035	0.15–0.30	0.40–0.60 Mo

6. Marine boiler steel plate. Navy Department Specification 48-P-24	Grade A 60–70,000 Grade B 55–65,000	(4)		0.04 0.04	0.04 0.04	... ...	... ...
7. Chromium-manganese-silicon-alloy-steel plates for boilers and pressure vessels. A.S.T.M. A202–39 (A.S.M.E. S-28)	Grade A 75–90,000	0.17 max.	1.05–1.40	0.04 max.	0.035 max.	0.60–0.90	0.30–0.60 Cr
8. Low carbon-nickel-steel plates for boilers and other pressure vessels. A.S.T.M. A203–39 (A.S.M.E. S-43)	Grade A 65–77,000 Grade B 70–82,000 Grade C 75–87,000	0.17 max. 0.20 max. 0.25 max.	0.80 max.	0.04 max.	0.035 max.	0.15–0.30	2.00–2.75 Ni
9. Seamless steel or shell drum forgings. (A.S.M.E. S-4)	Grade 1 60,000 min. Grade 2 70,000 min.	0.35 0.35	0.40–0.90	0.04	0.04	0.15–0.30	...

NOTES:
(1) For plates 3/4 in. and under in thickness.
(2) For plates over 3/4 to 4 in., inclusive, in thickness.
(3) For firebox quality steel, made by basic open-hearth process.
(4) Carbon not specified in plate specification, but limited to 0.35% max. for fusion welding.
(5) Carbon content progressively higher for plates 1 in. and under, 1 to 2 in., inclusive, 2 to 4 in., inclusive, 4 to 6 in., inclusive, in thickness.
(6) Carbon content progressively higher for plates 1 in. and under, 1 to 2 in., inclusive, 2 to 4 1/2 in., inclusive, in thickness.
(7) Carbon content progressively higher for plates over 1 to 2 in., over 2 to 4 in., over 4 to 6 in. in thickness.

Item 5 covers three grades of steel to which molybdenum has been added. The strengthening effect of both silicon and molybdenum has here been utilized to produce a steel of high-tensile strength with lower carbon content. This fact is important from the standpoint of welding the higher tensile grades inasmuch as carbon of all the elements has the greatest influence on the hardening characteristics and thus the weldability of steels.

Although steel conforming to this specification is being used for some boiler drums, its greatest value lies in the fact that the addition of approximately 0.50% molybdenum has imparted high-temperature properties far superior to those possessed by plain carbon steel. For this reason, carbon-molybdenum steel is peculiarly suitable for service at temperatures above 700° to approximately 1000°F. and is, therefore, an excellent material for superheater headers and tubes in modern high efficiency boilers.

Pressure Vessels Other than Boiler Drums.—In the petroleum and chemical process industries, the service conditions become more complex. The handling of corrosive liquids and gases will require the selection of a steel with appropriate resistance to the specific corrosive media. High-temperature strength and resistance to oxidation become more significant in view of the high operating temperatures sometimes required. In general, however, the steels shown in Table 4 may be used in the construction of fusion welded pressure vessels when corrosion is not an important factor and provided the temperature of operation does not exceed approximately 1000°F.

In this field, full advantage may be taken of the superior high-temperature properties of the carbon-molybdenum steel, A.S.T.M. A-204 (A.S.M.E. S44), for service at temperatures to 1000°F. For example, the allowable working stress for steel of this type remains constant to 750°F. compared to 650°F. for plain carbon steels, and at a working temperature of 950°F. the allowable working stress is approximately double that permissible with carbon steel (see Fig. 12). The economy of using carbon-molybdenum steel for pressure vessels subjected to stress at temperatures above 650°F. is apparent.

To illustrate the constructional advantages of high-tensile carbon steel (A.S.T.M. A212–39) for service below 650°F., and of carbon-molybdenum plate (A.S.T.M. A204–39) for service above that temperature, let there be assumed a drum 50 in. in diameter, a working pressure of 900 psi., and a weld joint efficiency of 90% with a factor of safety of 5. For service at 650°F. or below, this drum if made of 55,000 to 65,000 tensile carbon steel would be approximately 2.3 in. thick. If made of high-tensile plate of 70,000 minimum tensile strength, it would be 1.8 in. thick, and if made of carbon-molybdenum steel of 70,000 minimum tensile strength, it would also be 1.8 in. Note that for this service the carbon-molybdenum steel shows no advantage over the carbon steel of similar strength for the reason that up to this temperature (650°F.) the room temperature properties apply on all steels. If the service temperature is 800°F., the shell thickness in the first instance would be increased to 3.1 in., the high-tensile plate to 2.5 in., while the carbon-molybdenum steel requirement would remain at 1.80 in. for now the superior high-temperature properties of molybdenum steels apply.

Let it now be assumed that the service temperature is 950°F., the other factors remaining unchanged. In such case, the lower tensile carbon steel

would be the impractical thickness of 9.6 in., the high-tensile carbon steel 6.6 in. and the carbon-molybdenum steel a reasonable 3.1 in. thick.

Steels containing 4 to 6% chromium with 0.50% molybdenum combining high-temperature strength with improved corrosion and oxidation resistance have demonstrated their value particularly for still tubes and the like. Such material has been used in pressure vessel construction to a limited extent, but exceeding care must be used in welding and inspection. This material has extreme air-hardening properties resulting in hard and brittle welded joints. Normal heat treatment for the relief of stresses alone is not sufficient to fully correct the hardened condition. For this purpose, a full anneal at approximately 1500°F. followed by a retarded furnace cooling is required. Preheating the structure to 400° or 500°F. is recommended and during the welding operation this preheat temperature should be maintained.

Materials Used for Low-Temperature Service.—Certain processes, typically the dewaxing of oil in the petroleum industry and the manufacturing of dry ice, require pressure vessels, pressure filters and solid CO_2 chambers which operate at sub-zero temperatures. Those plants not only operate at low temperatures, −40 to −75°F. in the dewaxing process and as low as −112 to −150°F. in some chemical processes, but at high pressures as well. Since large quantities of refrigerant are carried in the system and since the vapor pressure of the refrigerant or product is low, the potential danger incident to failure is great, and extreme care should be exercised in the selection of materials. Although the tensile properties are not materially affected, carbon steel suffers a loss in notch toughness or impact strength and is ordinarily not suitable for pressure vessels operated at low temperatures. Carbon steel plate which at normal temperature may possess a Charpy impact value of 25 to 30 ft.-lb., may show at sub-zero temperatures the extremely low value of three ft.-lb. or less, whereas the rules may require a minimum of 15 ft.-lb. Charpy in both plate and weld metal for pressure vessels operated at low temperature.

However, low carbon steel plate can be produced which will possess satisfactory notch toughness at the temperature of dry ice, −112°F., if the melting, deoxidizing, rolling and heat-treating practice are carefully controlled. Silicon killed steels have better notch toughness than rimmed steels, and thoroughly killed steels containing aluminum or other strong deoxidizer apparently are tougher at lower temperatures. Better and more uniform low-temperature properties are obtained with low carbon low alloy steels, a typical example being the 2.00 to 2.75% nickel steel A.S.T.M. Specification A203–39, Table 4. This steel will give satisfactory low-temperature impact strength at temperatures as low as −100°F. Welding of this steel is successfully carried out with the weld metal also satisfactorily meeting impact requirements.

Other low alloy steels which are being used in increasing amounts for low-temperature service are the chromium-copper-nickel steels, the manganese-vanadium steels and the chromium-manganese-silicon steels A.S.T.M. A202, Table 4. Grain refining elements such as aluminum, vanadium and zirconium have proved desirable additive agents for improving the low-temperature properties of steel.

High alloy steels of the austenitic type (18 chromium–8 nickel as a typical

example) possess low-temperature properties of a much higher order and lend themselves readily to welded construction.

In the non-ferrous group, copper and copper alloys, nickel and nickel-copper alloys possess high notch bar values at temperatures as low as −175° F. In fact, both the high alloy austenitic steels and the non-ferrous group named above, in general, lose little, if any, of their notch toughness until extremely low temperatures are reached, and both types are readily fabricated by welding.

Corrosion-Resisting Linings and Clad Plate.—The corrosive conditions incident to oil refining and chemical process industries require, when such conditions are severe, that the pressure vessel be provided with a corrosion allowance which will permit safe operation of the vessel during its calculated useful life. Allowance for corrosion is made by increasing the thickness of the vessel above that required by the stress-temperature conditions. Periodic inspection determines when the allowable corrosion has been effected and beyond that point, the vessel must either be discarded or operated at reduced efficiency. To avoid the necessity of increasing the thickness of the steel plate to provide a corrosion allowance for a limited life, various types of corrosion-resisting linings have been developed. Depending, of course, on the corrosive medium and the composition of the lining, these linings are usually thin ranging upward in thickness from a few hundredths of an inch. Rarely do they exceed $^1/_8$ in. thick. A vessel provided with a lining which resists corrosion is designed to withstand only the operating stresses and no allowance in thickness is required for corrosion. When corrosion-resisting linings are uniformly fused to the base steel plate, the full thickness of the steel and certain approved linings may be used in calculating the thickness of the composite plate required. Alloy linings intermittently attached to the parent plate and which provide a shear strength of less than 20,000 psi. between the alloy lining and the plate may not so be considered and the thickness of the steel plate must be sufficient to carry the stress.

Alloy-lined or clad vessels are, therefore, lighter in construction and also possess a longer useful life generally than unlined steel vessels which are subjected in service to corrosive conditions and for that reason, require as corrosion allowance a considerable increase in plate thickness to provide a useful life of reasonable duration.

Furthermore, the corrosion that takes place in an unprotected vessel subject to corrosive conditions is frequently not uniform and localized corrosion may result in the early necessity for repair, discard or operation at reduced pressures. Extremely localized corrosion may be repaired by welding provided the proper authorities are aware of the extreme care required in the inspection of such repair to assure the continued safe operation of the vessel.

Practically any corrosion-resisting sheet material can be applied as cladding or lining to the parent steel plate. Most common are the stainless chrome irons and steels, the austenitic chrome-nickel steels and pure nickel. Lining or cladding is generally attached to the parent steel plate in the flat before forming, but may be applied by plug welding after the steel vessel has been fabricated. For special purposes, pure silver has been used as cladding material. Clad and lined plate is readily fabricated by welding

to conform with the requirements of the various regulations applicable to pressure vessel construction. Obviously, the lining intended to protect the baser material from corrosion must form a homogeneous whole and joints in the lining or cladding must have equal corrosion-resisting properties and be free from defects which will permit penetration of the corroding medium (see Chapter 26).

Multi-Layer and Banded Vessels.—These vessels are particularly adaptable for use at high pressures. The shells are made up of a multiplicity of layers of steel plate, each layer being wrapped around the one which precedes it and welded together at its longitudinal edges. The thickness of each layer is generally less than $^1/_4$ in. except the innermost layer which usually is somewhat heavier. Only this innermost layer need be leak proof. Telltale holes are employed to make sure that any leakage of the inner layer would be shown on the outside of the vessel.

The ends of the multi-layer shells are machined for welding, and adjacent shell courses or solid heads are attached by circumferential welds in the same manner as when working with solid plate.

In another design, the inner layer is made about one-half the thickness of the shell and the hemispherical heads are attached to the inner layer. This inner vessel is designed to take all stress in a longitudinal direction and all welds are completely X-rayed and stress-relieved. Outer layers of thin plate are wrapped around the inner vessel to a sufficient thickness to take care of circumferential stresses.

Fabrication—Shop Practice

Inspection of Plate.—Although all plate used in the construction of boiler drums and pressure vessels is inspected at the mill, it is advisable to inspect carefully the surface of all plates in the shop before starting fabrication. In this respect, sand or shot blasting is an excellent aid to shop inspection, particularly in the heavier plate. Adhering mill scale often hides surface imperfections such as scale pits, rough areas or surface laps which must be removed by grinding, and this operation is more economically accomplished in the flat.

It is desirable that the thickness be slightly greater than that required in the design, particularly in plates that require shop normalizing, and in plates heavy enough to require hot bending to compensate for the oxidation loss during heat treatment.

Layout and Preparation for Forming.—Most plates for shells or shell courses of single-plate construction are laid out to size in the flat and the welding groove planed on all four edges before forming.

The longitudinal edges of all plate up to $1^1/_2$ to 2 in. thick may be prepared for welding before forming, but greater accuracy may be obtained in the assembly of multiple plate shells if planing is done after forming. All plates in shells of two or more plate construction requiring cold forming or a combination of hot and cold forming if not machined for the weld groove, are planed square on the ends to remove edge tears on sheared plate, and notches in flame-cut plate, which may act as nuclei for failure during bending. As a rule, longitudinal welding grooves in all except low pressure shells for boiler drums requiring two or more plate construction, are planed

after forming while the circumferential welding grooves are turned after the longitudinal seams have been welded. Shells of courses for large diameter pressure vessels are more awkward to handle and the plates are more economically grooved for welding in the flat.

If plate is to be formed by pressing, center lines are laid out at the ends of the plate. From these centers, equally spaced registration points are laid out extending to the longitudinal edges of the plate. These registration points are numbered at each end so that the markings correspond, thus facilitating lining up the plate in the pressing die and avoiding a troublesome twist in the pressed shell.

Forming.—This is done either by rolling or hot and cold pressing in a hydraulic press. Cold rolling is limited by the equipment available and is usually limited to circular shells or shell elements under $2^1/_2$ in. in thickness and less than 25 ft. in length.

Some code rules prohibit the placing of tube holes or other unreinforced openings in, or closer than a certain specified minimum from, a welded seam. This rule may prohibit the construction of boiler drums in circular courses which require intermediate circumferential welds in the shell, when such welds would interfere with the tube hole pattern. Boiler drums, therefore, of 30, 35 and even 40 ft. in length are sometimes constructed of plate elements extending the full length of the shell.

Dependent upon the capacity of the press and the required diameter of the vessel, plates to $2^1/_2$ in. or greater in thickness, and of any required length, may be pressed cold. In this connection, however, although the ductility of the plate has been demonstrated by test coupons tested at the mill, including a cold bend to 180°, there is a definite limit to which a long plate may be cold formed without danger of cracking. For this reason, in cold forming, it is advisable to set a safe limit beyond which a plate should not be bent without an intermediate heat treatment to remove the effect of cold work. The pressing operation, therefore, may be carried out in stages, each bending stage being limited to a degree dictated by experience for each class of plate. A safe limit depending on material will normally range from 4 to 6% elongation at the outside surface. If the required radius with respect to plate thickness requires more than this amount of elongation, the unfinished plate is subjected to a stress-relieving treatment at 1100 to 1200°F. after which the bending operation may be repeated or completed depending upon the additional amount of bending required.

Boiler drums and pressure vessels are designed to meet individual requirements. There can, therefore, be but little standardization in the pressing operation due to the variety in drum diameters and plate thicknesses required. Standardized pressing dies for each diameter and plate thickness are out of the question from a cost standpoint. Excessive die cost is avoided by pressing in relatively narrow dies along successive longitudinal elements of the plate until the curvature of the plate corresponds to the required template or sweep. This method introduces certain flexibility in the pressing operation and permits one set of dies to be used for a variety of plate thicknesses thereby reducing the number of dies required in the shop.

Above $2^1/_2$ in. thick, the plates may be either hot rolled if the length and thickness do not exceed the capacity of available rolling equipment, or

may be hot pressed. In either case, plates are heated to a temperature slightly above the upper critical range which operation then also serves as a grain refining normalizing treatment for heavy plate.

The operation for hot pressing is essentially similar to cold pressing. Hot-pressed plates often require cold sizing under the press to correct slight variations from true cylindrical form.

Preparation for Welding—Welding Groove.—In plates of limited thickness, the edges are usually prepared in the flat. This method is also preferable in plate for heavy shells made from a number of courses, each course consisting of a relatively short cylinder consisting of a single plate. From the standpoint of cost, this practice is desirable but consideration must be taken of the elongation of the plate during forming in order to obtain the desired inside circumference. Otherwise, the specified diameter tolerance may be exceeded. In long heavy plate when the design requires two or more longitudinal elements, the weld grooves may be prepared after forming and close diameter tolerances may be held, and in boiler drums designed for a thick tube sheet and thinner wrapper sheet, this method is recommended.

The welding groove may be shaped by flame cutting or by planing. The latter is preferable for boiler drum tube sheets that require a smooth taper to conform to the thickness of the companion wrapper plate. Most generally used is the single U-type of welding groove with a $^1/_8$-in. root face at the bottom curving with $^1/_4$ to $^5/_{16}$ in. radius to a straight wall sloping approximately $^1/_8$ in. per in. to the outside surface of the plate.

Some conventional types of weld grooves are shown in Fig. 15-A. The full single U-groove permits weld metal deposition the full thickness of the plate from the outside and lends itself readily to automatic as well as manual welding.

Assembly of Drum Plates.—In assembly of drum plates for welding, the edges of the plates are brought together and tack welded into position. The inside edges of the plate which form the bottom of the welding groove may be in contact or may be left open $^1/_{16}$ to $^1/_8$ in. to permit greater weld penetration. Depending upon shop practice and the particular type of welding groove used, a mild steel backing strip of convenient size ($^1/_4$ in. thick x 1 in. wide) may be stagger welded on the inside of the shell and if the construction is not too heavy may serve to hold the shell in position for welding. For heavy plate construction, it will be necessary to weld assembly bars across the joint on the inside of the shell. These bars need be only heavy enough to hold the shell plates in position and permit handling of the shell for welding and should have sufficient flexibility to contribute nothing to the rigidity of the joint. The backing strip should be fitted as closely as possible to the inside surface of the plate on each side of the joint to be welded and is of distinct advantage when automatic welding is employed. In manual welding, the backing strip may be eliminated and double U-grooves of symmetrical or unequal depth may be used.

The stress due to weld contraction along and across a welded joint may be of yield point magnitude and the "pull" thus created tends to distort the plate at and adjacent to the weld, particularly in a circumferential direction. The normal effect of this weld contraction is to depress the cylinder at the joints so that the out-of-round tolerance allowed by the various rules is

exceeded. In light plate the out of roundness so obtained is readily corrected by rerolling to a true cylinder after stress-relieving the shell and before X-ray inspection if such is required. In heavy plate construction, however, any departure from circularity in the welded shell beyond the tolerance of 1% of the diameter usually allowed, is corrected with difficulty by means of jacks or struts. It is, therefore, desirable to prevent such distortion as far as possible in heavy plate construction by allowing for this condition during pressing, by opening the chord across each element of the

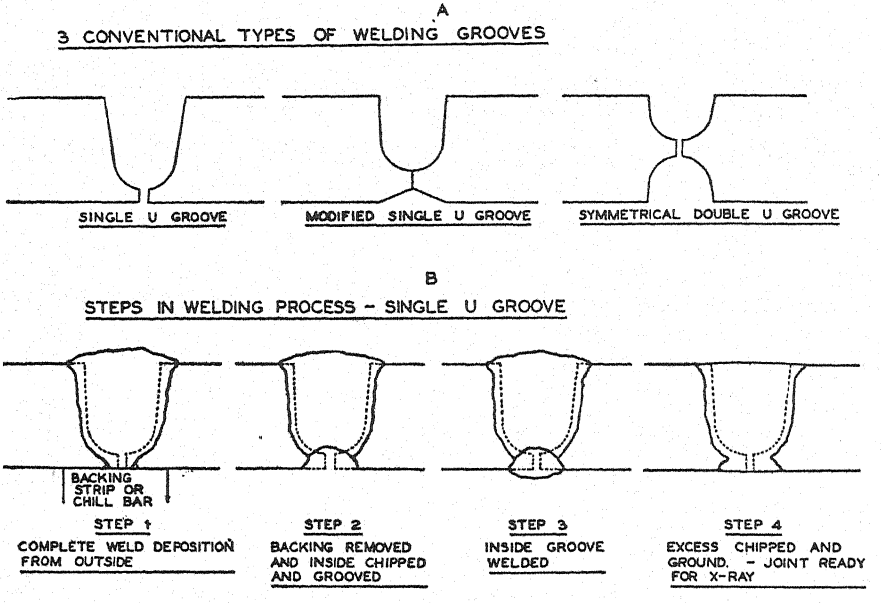


Fig. 15—(A) Three Conventional Types of Welding Grooves. (B) Steps in Welding Process—Single U-Groove

assembly and by placing supporting struts at the joint during assembly and welding of the cylinder. Test plates required by the various codes are attached to the ends of the assembled shell in such manner that the welding groove in the test plate is a continuation of the longitudinal welding groove in the shell.

Welding.—Welding may be done either by hand or by automatic welding machine by operators who have passed qualification tests recognized by the various codes. One-quarter-inch diameter electrodes are recommended for butt seam welding and may be used even for the first bead or layer, provided a backing strip is used to cover the under side of the joint, or if the projecting shelves forming the bottom of the groove are relatively heavy. If these are light and no backing strip is used, it may be necessary to use lighter electrodes when depositing the first bead to avoid "burning through" which may take place when heavier electrodes and consequently higher welding amperages are used.

The welds are built up in relatively thin layers approximately ten layers per inch of thickness. The beads are deposited either in straight longitudinal ribbons, or the electrode tip may be oscillated from side to side to cover the full width of the welding groove. In either case, the edges of the bead should fuse evenly into the walls of the joint or into the surface of the previously deposited weld. Sharp depressions or heavy shoulders at the edges of the bead caused by excessive convexity of the bead due to insufficient welding heat, or to the use of the wrong type of electrode and under cutting at the walls of the joint, should be avoided as factors which are the primary cause for entrapped slag inclusions.

The relatively thin layers or beads of weld metal permit a progressive grain refinement of preceding layers, eliminating the columnar structure characteristic of single beads of weld metal as deposited. The effect of this grain refinement in normal arc weld metal is an improvement in ductility and impact resistance.

Satisfactory welding results may be obtained with either direct or alternating current as the source of heat. However, welding with alternating current transformers and reactors has a distinct operating advantage over direct current welding in that the occasional troublesome arc blow is entirely absent in the former and welding may be started at one end of a seam and progressed uniformly to the other end without encountering magnetic influences which appreciably affect the arc. Welding electrodes may be obtained which work equally well with both.

In rigid types of structure such as encountered in welding the seams in heavy drums or attaching nozzles to thick shells or heads, it is advisable to weld continuously until the joint is finished to avoid as much as possible the tendency for cracks to occur in welded seams of such construction.

Although the metallic arc multiple bead deposition method as briefly outlined above is predominant in pressure vessel fabrication, particularly in the higher pressure and/or higher temperature range of application, other approved methods of fusion welding are being applied to pressure vessel construction. Although modifications in technique and design of joint may be necessary, the essential requirements will remain the same.

Carbon Arc Welding.—For vessels up to a limiting thickness of approximately $^3/_4$ in., the carbon arc process may be applied to a square cut butt joint. Weld penetration is sufficiently great so that for this thickness a single pass of the carbon arc on each side of the plate completes the weld. Only sufficient filler metal is used to build the weld slightly above the plate surface. For heavier plate, suitable modifications must be made in the procedure and in the design of the joint to be welded. (See Chapter 4D).

Gas Welding.—Oxyacetylene gas welding may also be applied to the construction of pressure vessels of limited thickness, and good quality weld metal is obtained by properly trained operators. Gas welding is particularly suitable for the butt welding of tubes and pipe, and with skilled manipulation of the welding torch and proper design of the welding groove, thorough penetration may be obtained at the root of the weld without the use of a backing ring.

High-Amperage Single-Pass Welding.—This method feeds automatically a bare electrode through a powdered mass of special flux which completely fills the welding groove and covers the arc. The diameter of the electrode,

the welding amperage and the speed of electrode travel are so controlled that the full thickness of the joint, including built-up excess weld metal, is completely filled up in a single pass. The method is rapid and good results have been obtained in plate thickness of 2 in. or more. The physical properties reported for this type of weld metal have met the various code requirements for high-tensile 70,000 psi plate as well as for the low-tensile 55,000 plate.

Basic Principles of Welding—Metallurgy.—The basic principles involved in the successful welding of any pressure vessel steel may be stated as (1) keeping the stress imposed by the thermal conditions of welding to a safe minimum, and (2) eliminating or correcting the quench effect of rapid cooling from above the critical temperature.

Except in very rigid joints in heavy plate, the thermal stress and the quench effect in low carbon steel are ordinarily so limited that the weld metal and affected zone possess sufficient ductility to permit adjustment to the stress introduced. In the higher carbon or low alloy steels of greater tensile strength, however, rapid cooling may so increase the hardness and reduce the ductility that difficulty may be encountered. This may be explained by a brief but fundamental statement of the mechanism of weld and affected zone hardening in carbon steel. The same principles will apply on low alloy steels, although less carbon is generally required to bring about similar results.

As steel is heated above its transformation temperature, an atomic rearrangement takes place and a solid solution of carbon in iron, called austenite, is formed. As this austenite cools, a reverse atomic change takes place, and the carbon is thrown out of solution to form a mixture of iron and carbide. The more rapid the cooling, the more the carbides are dispersed, and the harder the steel becomes. If the composition is such, and the rate of cooling so rapid, that some of the solid solution (austenite) is still untransformed when a temperature of 350 to 400°F. is reached, it will then transform directly into the very hard and brittle structural constituent called martensite.

During welding, the weld metal and a narrow zone in the base metal adjacent to the weld are heated above the transformation point of the steel. The width of the zone is governed by the heat input, speed of welding and mass. Due to the usually great mass of relatively cool metal in proportion to the extremely local heating, cooling takes place very rapidly—in effect, the steel is quenched and corrective measures must be taken to modify the structural characteristics of the weld zone to permit an adjustment to the stresses introduced, without fracture.

Preheating.—Logically, these corrective measures should be directed toward the elimination of the quench effect by retarding the cooling after welding to permit complete transformation of the structure at a temperature above that at which the very hard and brittle structural constituents form. Inasmuch as degree of hardness is influenced by rate of cooling and magnitude of stress is influenced by the temperature differential or gradient, preheating will accomplish the double duty of reducing both.

Heating prior to and during the welding of relatively heavy drum plate may therefore be advantageously applied to prevent the formation of stress cracks and fissures in the weld. This is particularly important in welding

the higher carbon high-tensile steels and the low alloy steels which are now being used in drum construction and which have a tendency toward air-quench hardening. The preheat temperature required depends on the mass and rigidity of the joint and the type of plate material used and, in general, preheat temperature need not exceed 300°F. When welding extremely air-hardening materials such as the 4 to 6% chromium, 0.50% molybdenum steels, the preheat temperature may be advantageously raised to 400 to 500°F.

Double-Welded Joints—Excess Weld Metal.—Codes covering the construction of boiler drums and pressure vessels for severe service, require that welding be done from both sides of the welded joint. The single U-groove is acceptable under this classification provided there is complete penetration and reinforcement on both sides of the joint. The inside of the weld is usually chipped to sound metal and the groove thus formed is re-welded. This practice is recommended in any type of welding groove, i.e., the side opposite that from which the first body of weld metal was deposited should be chipped and grooved before rewelding to eliminate initial defects in the first bead deposited. Figure 15-B illustrates the steps in welding the single U-groove when a backing strip or chill bar is used.

Both inside and outside welds in the main joints are built up approximately $^1/_8$ in. above the plate surface. Rules differ with respect to the removal of this excess unrefined weld metal. Some specifications require that the excess, both inside and out, be chipped and ground approximately flush with the plate surface. For the purpose of inspection of welds, this practice is recommended, particularly for heavy shells and for welds joining a thick tube plate to a thinner wrapper plate in boiler drum construction (Fig. 6-C).

Heads—Assembly and Welding.—In intermediate and heavy shells, the ends of the cylinders are prepared for welding by cutting the welding groove in a boring mill or lathe, the same type of groove being machined as used in the shell. To eliminate troublesome fitting up and welding problems and for the sake of appearance, the circumferential travel (measurement) of heads and shell should be as close as good shop practice permits.

Heads are assembled to the shells with or without the backing strip or ring, but here again the backing strip is a distinct advantage if full automatic welding is employed. Welding procedure for head seams is the same as for longitudinal seams except that for automatic welding it is necessary and for hand welding, very convenient to have the drum placed on power-driven drum turners so that the drum rotates under the stationary electrode. As in longitudinal seams, the inside is chipped and grooved to sound metal and rewelded.

Nozzle Welding.—It is advisable to weld all required pressure part attachments, such as nozzles and pads, to heads before the heads are assembled to the shell. At this stage, the heads may be conveniently handled and all welding may be done in approximately the down-hand position. On the other hand, it is more convenient to weld nozzles, pads and other external connections to the shell after the heads have been welded and after X-ray inspection as these may interfere with the manipulation and rotation of the drum during welding, and with X-ray inspection of the welded seams.

Nozzles and internal or external connections to pressure vessels are usu-

ally welded manually and the structure is so manipulated that the welding is done in the most convenient position. When stress relief of the vessels is required, all welded connections are attached prior to this operation. Rules differ with respect to the method of attaching nozzles. Some rules or specifications require through welds, thus making the nozzle an integral part of the structure. In this case, the wall of the shell or head is V'd to permit complete penetration and, as in main seam welding, it is advisable to back chip the weld before completing the joint to remove defective material or to remove undesirable notches or irregularities in the first metal deposited. In the event that a reinforcing ring around the nozzle is required, this also is welded the full thickness of the reinforcement and the depth of the weld becomes the combined thickness of the vessel and the reinforcing ring. The weld around the nozzle is finished off as a fillet weld on the outside of the vessel and also on the inside if the design is such that the nozzle has an inside projection. Nozzle re-enforcing pads may be single rings or, for large openings and high pressures in order to obtain a more uniform stress distribution, may be built up of two or more rings, each ring above the first being smaller in area than the one below. Each ring besides being welded to the nozzle neck is fillet welded at the periphery to the structure below it.

Other rules permit nozzles to be inserted in an opening with slight clearance, and attached by fillet welds of predetermined size, both on the inside and on the outside of the vessel wall. Here also, nozzle-opening reinforcing rings are used if stress calculations show them to be necessary. Inasmuch as all nozzles are part of the pressure unit, they require welding of first quality and the same care must be used as in welding the longitudinal and circumferential joints.

Stress Relieving.—All boiler construction codes require that the internally stressed condition caused by the welding operation be eliminated by subjecting the completely welded vessel to a heat treatment at elevated temperatures. Codes covering the construction of other classes of pressure vessels may or may not require such thermal treatment depending on the nature of the service, the thickness of the vessel and the desired welded joint efficiency. To avail of the highest joint efficiency relief of stresses is required. The stress-relieving treatment usually consists of heating the welded vessel at a uniform rate to a temperature of 1100 to 1200°F., holding at that temperature for a period of 1 hr. per inch of thickness, and then cooling uniformly in still atmosphere. While some codes permit local heat treatment of girth joints for stress-relieving those joints only, the general practice in stress-relieving is to heat the vessel as a unit.

The usual stress-relieving treatments do not produce any appreciable changes in the microstructure of either the plate material or weld metal. Some slight spheroidization of the carbide constituent will occur in the plate material, which will result in a slight reduction in its yield point and tensile strength and in a slight increase in its ductility. The average reduction in the tensile strength of the plate material will be about 5%. Stress-relieving heat treatment also results in a slight softening and increased ductility of the weld metal. Such changes in physical properties of both plate and weld metal are only incidental, the primary purpose of the heat treatment being the elimination of the internal stresses, which can seriously affect the serviceability of the drum.

The principles of thermal stress relief are based on the fact that the elastic properties of a steel are so materially reduced at the temperatures specified for stress relief, that a plastic readjustment is permitted at the stressed regions. Followed by uniform cooling, the residual stress in the finished structure can be no higher than the yield point of the steel at the stress-relieving temperature.

In view of the marked softening and lack of strength at 1100 to 1200°F., it is necessary to provide suitable support in the furnace to very long heavy vessels or for vessels having a large diameter-plate thickness ratio. Sagging and distortion through plastic flow induced by the weight of the vessel can be prevented by suitably spaced saddle supports which provide a large bearing surface, and by internal struts across the diameter.

Radiographic Inspection.—All codes covering the construction of boiler drums require the main welded seams to be radiographed. Radiographic inspection on all other classes of pressure vessels is optional depending upon the service requirements and the joint efficiency desired. The highest joint efficiency is permitted if both stress relief and radiographic inspection are practiced. As an aid to radiographic inspection and the interpretation of the X-ray film, it is recommended that both surfaces of the welds in the main seams of pressure vessels which have been built up approximately $^1/_8$ in. above the plate surfaces be chipped and ground approximately flush with the plate surfaces. This operation gives a uniform thickness across the weld and removes surface irregularities which may interfere with proper interpretation of the X-ray film.

Welded joints may be radiographed by means of X-ray machines specially constructed for the purpose, or the source of radiation may be radium or radium emanation capsules. X-ray machines up to a million volts are available whereby it has become economically practicable to examine welded joints 5 or 6 in. thick and more.

The following briefly outlines the conditions specified for radiographic inspection:

1. All welds containing cracks and zones of non-fusion, regardless of extent, are unacceptable.
2. Welds containing entrapped slag bodies with length in excess of $^1/_3T$ (where T is plate thickness) are unacceptable.
3. Welds in which radiographs show porosity shall be judged as acceptable or unacceptable by comparison with a standard set of radiographs.
4. The technique must be such that defects with thickness equal to or greater than 2% of the plate thickness are revealed.

X-ray inspection of nozzle welds is generally not required but may, in some instances, be specified. Increased care and judgment are required in the preparation and interpretation of nozzle radiographs. The design of the joint, the angle of the scarf, the variation in mass and the probable orientation of a crack must be considered in an approach to nozzle weld radiography.

A useful aid in the inspection of nozzle welds is the sometimes specified practice of polishing and etching the surface of a weld for indications of surface cracks. This test may be augmented by testing the weld surfaces by the magnetic powder method. This last is useful in checking the complete removal of defects in required repairs or when back chipping the inside of welded joints before completing the welding operation.

Unacceptable defects in a welded joint must be removed, usually by chipping, and rewelded. The area at and adjacent to the repair in longitudinal and circumferential welds requires radiographic inspection if that was required for the original joint. Similarly, the vessel must be stress-relieved after all welding repairs are made.

Physical Tests.—Production welded test plates required by the various codes are treated in accordance with the rules specified for the fabrication of the parent vessel, i.e., thermal stress relief and radiographic inspection may or may not be required. From these test plates, the various tension and bend tests are removed and these must meet certain minimum requirements which are based on the properties of the plate used in construction. Failures to meet the requirements are very rare and indicate the excellent quality of weld metal produced in welded seams.

After stress relief, if this is required, pressure vessels are hydrostatically tested at one and one-half times the working pressure and, while under this pressure, are subjected to hammer blows at 6-in. intervals along the longitudinal and circumferential welds. When testing drums for power boilers, and unfired pressure vessels, this test is followed by a hydrostatic pressure of twice the working pressure of the vessel.

Thin Wall Pressure Vessels.—The foregoing discussion has largely applied to pressure vessels of relatively heavy wall. Although essentially similar with respect to fabrication, the manufacture of welded vessels of thin wall thicknesses approximately $^1/_4$ in. or less presents certain problems peculiar to this class of vessel.

Automatic or semi-automatic equipment is usually employed and the weld is finished in a single pass. Metallic arc, carbon arc, atomic hydrogen or gas flame may be used and special clamping devices are required to hold the longitudinal welding edges of thin-walled cylinders in proper alignment. Backing bars permanently affixed to the inside wall of the joint, or removable chill bars are used to permit complete penetration of the weld metal. These should fit snugly the inside surface across the joint and the abutting edges and the backing bar should be clean. For economy in fabrication, it is essential that the single bead forming the joint be free from pinholes, slag and non-fusion which will show up as leaks on subsequent testing operations. The abutting edges of both longitudinal shell seams and circumferential butt-welded head seams must be in close alignment both from the standpoint of appearance and sound welding practice. For this reason, the difference in the circumferential measurement of the shell cylinder and the flanged head must be held within close tolerance.

Distortion of the cylinder, by reason of the welding operation, is readily corrected by rerolling to a true cylinder. It is important, however, that the plate adjacent to the welding seam be bent or "bull-dozed" to true circularity as an aid to correct a tendency to form a longitudinal peak at the weld. Welding speeds and parallel adjustment of the welding groove may be governed by experience on similar classes of work. In $^1/_4$-in. plate, there is usually no necessity for scarfing the abutting edges. These may be sheared square and the edges left open to a degree which will permit thorough penetration at the joint.

Nozzles and bosses or pads are usually fillet welded by hand to the shell wall or head of the vessel. When welding pads on vessels of 14 gage or

under, it may be necessary to provide chill pads on the opposite surface to prevent burning through.

Such vessels are often not built to any code ruling and, except when specified by the customer by reason of the service conditions or the material used, X-ray and stress relief are not required. Due to the relatively high cost of repair compared to making the single bead weld in thin vessels, the importance of careful planning, supervision and inspection cannot be overemphasized. In general, the nick-break and the guided bend tests are the most useful in controlling the quality of welding in thin vessels and should be used periodically in checking the performance of operators and machines. The reverse or back bend is extremely useful in checking the degree and quality of weld penetration.

The methods used by different tank manufacturers may seem on the surface to be very different; however, on close examination it will be found the underlying principles are about the same. Continuous watching and checking of operators and machines is required, with close and continuous attention to small detail. Neat fits everywhere are imperative. It is difficult to bridge a gap, whether in a main seam, or at a boss or where a coupling or nipple is attached. Not only the surfaces to be welded but the material itself must be clean. All necessary equipment for either machine or hand welding should be maintained in excellent condition. It is the experience of all manufacturers that for single bead welding it is cheaper to do the job right the first time. Repair and retesting are more expensive than many realize, and it is more economical to spend a little more on the fabricating end if it will save on the test floor.

Economizers, Superheaters and Heat Exchangers.—Such units generally involve parallel tubular elements extending between two or more headers or drums. The arrangement will vary widely for individual jobs.

Economizers are placed toward the low-temperature end of the passage of the heating gases and are used for heating the feed water before entering the steam generating portion of the boiler unit. The temperatures attained in service of economizer parts are, therefore, relatively low, and plain carbon steel is usually sufficient to meet the service temperature conditions. Superheater units are usually installed toward the high-temperature end of the heating gas flow. As their name denotes, superheaters raise the temperature of the steam delivered from the primary steam generating portion of the boiler unit. Superheater parts, therefore operate at relatively high temperatures, and in many installations the service temperatures attained require the use of the superior oxidation resistance and creep resistance of alloy steels. The same general remarks may also be applied to heat exchangers. Their function is the transfer of heat from one phase of the operation to another and conditions may be such that materials for high-temperature service are required. Materials of various compositions are utilized. Chromium, silicon and aluminum, or combinations of these elements, are preferred for increased oxidation resistance, and molybdenum or tungsten additions for increased creep resistance. The quantity of these elements present in the steel will vary, depending upon the maximum anticipated temperature at various portions of the superheater or heat exchanger.

Economizer and superheater headers are generally fabricated of tubular pipe stock or forged seamless drums, but may also be fabricated of rolled

and welded cylinders. The same is true of heat exchanger shells. Welding is involved in all cases, either in the closure of the ends or in the attachment of nozzles to shells or heads. In the case of very long headers, the required length may be obtained by fusion butt welding two or more short component parts. The rules for fusion welding as previously outlined are applicable to the construction by fusion welding of such parts.

The tubular elements in superheater, economizer and heat exchanger units may be longer than the mill length normally obtainable. In such case, the required length is obtained by butt welding together mill lengths of tubing. The butt welds are made by either flash or upset resistance welding or by fusion welding.

Field Welding.—In recent years, fusion welding has found increased application in the erection of pressure vessel units. Connecting pipes and pipe lines for various purposes are generally assembled by fusion welding in the field. Depending upon service conditions and the applicable specifications, butt-welded pipe welds may require both radiographic inspection and stress relief. When X-ray inspection is required, this is generally accomplished by using radium or radium emanation capsules as a source of radiation. Stress relieving of pipe joints is accomplished by locally heating the circumferential band at and adjacent to the pipe joint by means of gas flame, electrical induction or electrical resistance methods. During such local stress relief, there should be sufficient flexibility in the pipe assembly to permit unrestricted movement during the heating and cooling.

Under proper authority and regulation, superheater and economizer elements may be repaired in the field by fusion welding. Tubes may be seal welded at the tube sheet to avoid leakage in high-pressure units. Welded repair followed by machining, will correct defective or steam cut inspection or handhole seats. The supporting structure for the pressure unit is fabricated and erected by means of fusion welding. Localized corrosion pits or cracks which may have developed in pressure vessels during service may be repaired by welding provided the serviceability and safety of the vessel are not in danger and provided the provisions established by various controlling agencies are carefully followed.

CHAPTER 39

FIELD WELDED STEEL STORAGE TANKS*

General Characteristics, Use of Storage Tanks, Special Types, Typical Welding Details, Design, Selection of Storage Tanks, Rules for Field Welding of Steel Storage Tanks, Wrought Iron Tanks.

A SPECIAL type of structure for which welding is particularly suitable is that represented by a field constructed storage tank. Such tanks can be made absolutely tight by welding and welded construction is now generally used for these structures.

General Characteristics

In this discussion of a field welded storage tank as a special structure, the subject matter will be confined to the so-called large bulk storage tank, i.e., a tank too large for shop assembly, necessitating field erection. Such a tank has a diameter greater than 12 feet and is generally a vertical tank. By this is meant a cylindrical steel tank with vertical axis, designed to contain liquid products operating generally at atmospheric pressure or at not over 15 pounds per square inch gage pressure. This includes oil storage tanks of various types, standpipes, reservoirs and elevated tanks for the storage of water. Such storage tanks differ from most other common structures in one or more of the following items:

1. The load and resulting stress are uniform in direction and cannot change rapidly.

2. Due to the shape there is a low degree of stress concentration at critical points.

3. Prior to use it is possible to test a tank at its actual working stresses, and in most cases at stresses slightly in excess of the normal working stresses.

4. The shape and location of a storage tank generally permit thorough inspection of the shell at any time, even during use, and paint or other protection can be applied readily to surfaces subject to atmospheric corrosion.

5. Joints must be tight to prevent leakage of liquid.

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Use of Storage Tanks

With the growth of our cities and towns the demand for water storage has increased and the growth of the automobile and oil industries has increased the requirements for oil storage. These with other industrial requirements have developed a great demand for large field constructed storage tanks.

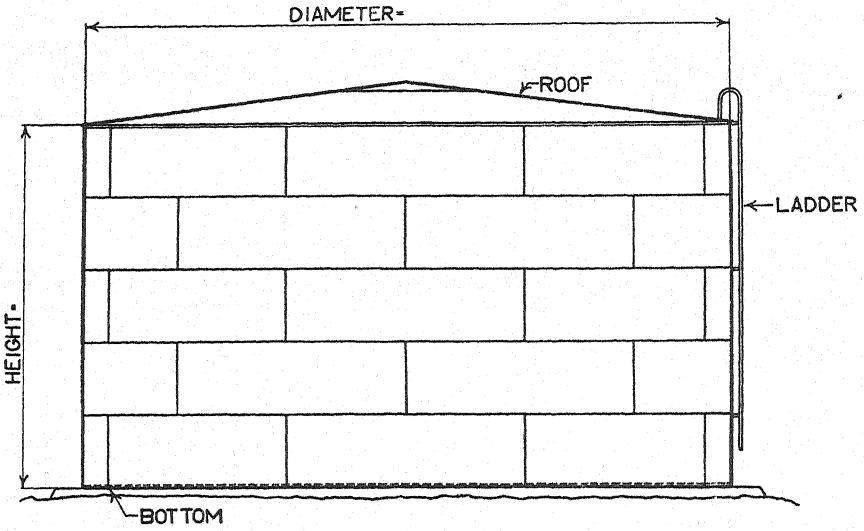


Fig. 1—Cylindrical Oil Storage Tank with Cone Roof

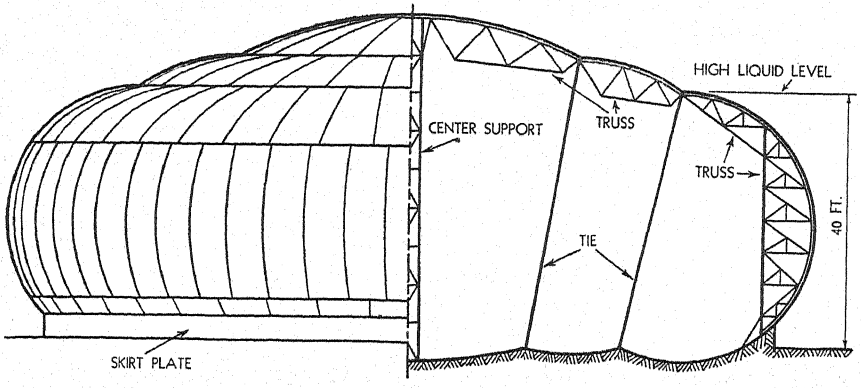


Fig. 2—Noded Spheroid for Storing Petroleum Products Under Low Pressure

Special Types

While the most common shape of tank is the vertical cylindrical tank with a cone roof, the need of preventing excessive evaporation losses on volatile oils has led to the development of special types of oil storage tanks differing in various details. Also in the case of water storage tanks it is sometimes necessary to elevate the tank on a tower in order to obtain suitable gravity head for distribution purposes. The more common types are as follows:

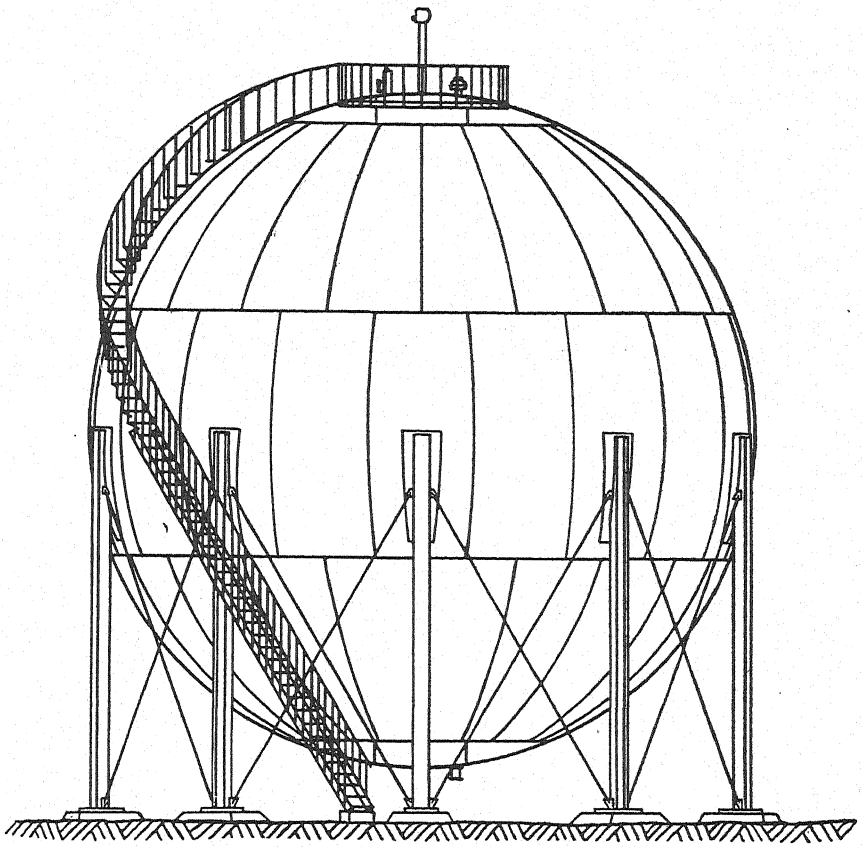


Fig. 3—Sphere for Storing Gas or Petroleum Products Under Pressure

1. Cylindrical oil storage tank with cone roof (see Fig. 1).

2. Noded spheroid for storing petroleum products under low pressure which permits a pressure above atmospheric on the surface of the liquid with nearly uniform stresses throughout the shell (see Fig. 2).

3. Sphere for storing gas or petroleum products under pressure which permits a pressure above atmospheric with nearly uniform stresses through-

out the shell. Such tanks are frequently built for a pressure range above 15 pounds per square inch gage pressure and in such case they become pressure vessels and should be constructed under the A. S. M. E. Unfired Pressure Vessel Code (see Fig. 3).

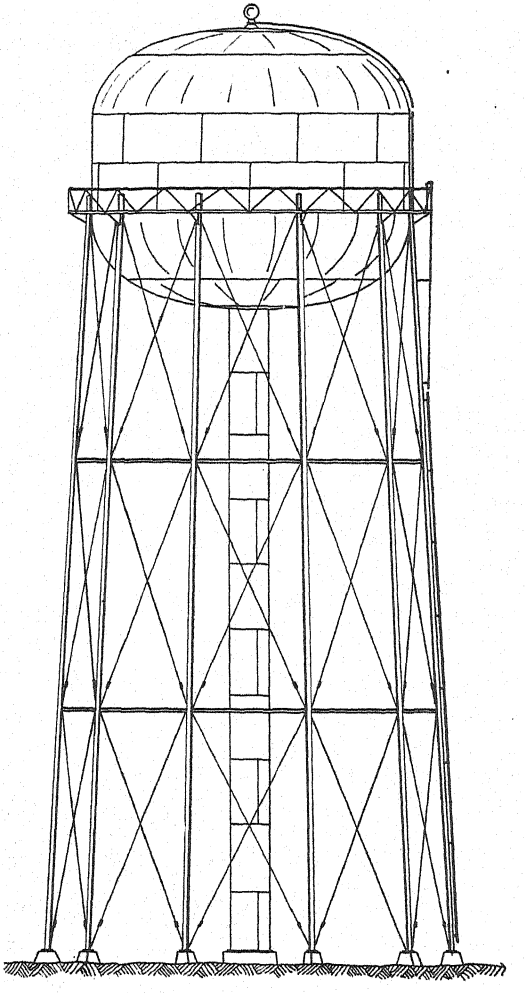


Fig. 4—Elevated Water Storage Tank

4. Elevated water storage tank (see Fig. 4).
5. Cylindrical water standpipe with dome roof (see Fig. 5).
6. Cylindrical water standpipe with conical roof (see Fig. 6).
7. Railroad water tank (see Fig. 7).

Each type of tank requires its special accessories such as foundations

vents, gages, drains, overflows, manholes, etc., depending upon the proposed content, local conditions and regulations. The design, construction and application of these accessories should be handled by men of experience in this field.

Typical Welding Details

Welding details should conform to the Code or requirements of the specifications under which the tank is constructed. Typical welding details for a tank constructed with butt-welded shell are shown in Fig. 8.

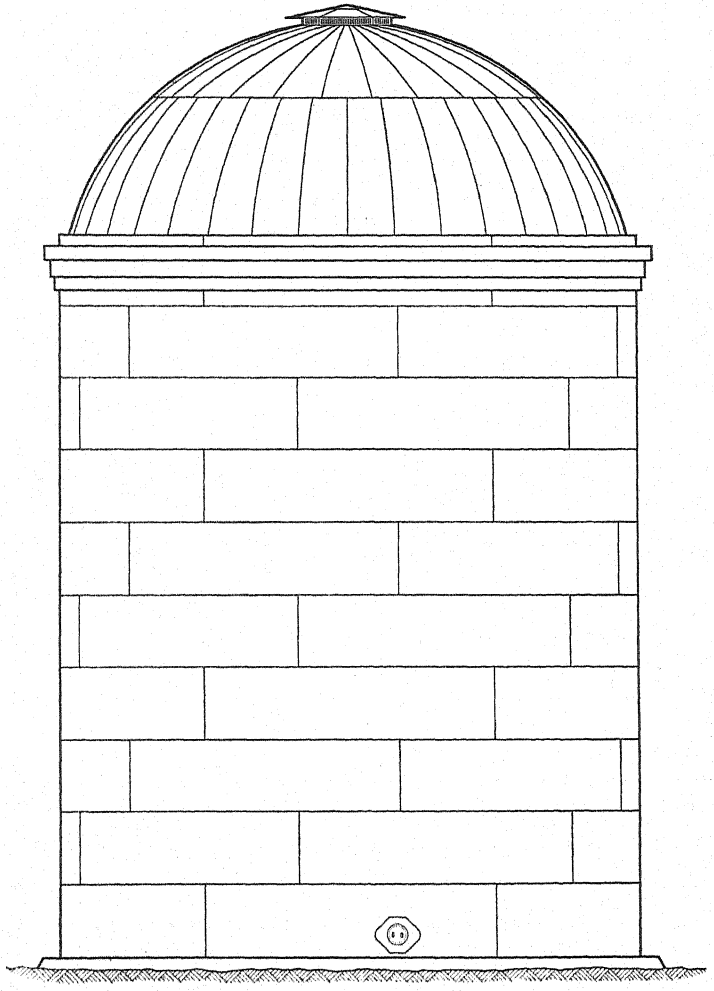


Fig. 5—Cylindrical Water Standpipe with Dome Roof

Design

Industry has recognized the importance of proper design of field welded storage tanks to the extent that several Codes have been written covering this subject. The AMERICAN WELDING SOCIETY has "Rules for Field Weld-

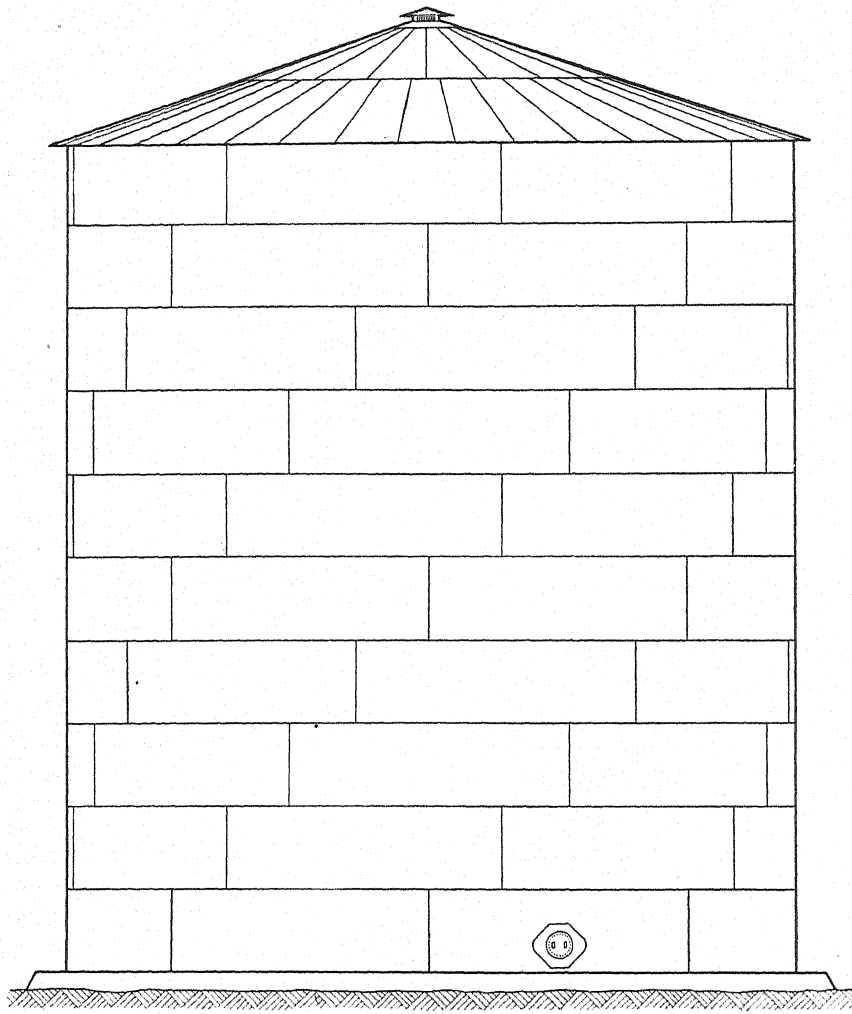


Fig. 6—Cylindrical Water Standpipe with Conical Roof

ing of Steel Storage Tanks" which cover the welding requirements for the construction of such tanks. These rules are included hereinafter. Other specifications have been prepared covering the design and construction of field welded storage tanks for particular types of product and service and

should be referred to for unit stresses and other applicable data. A list of such specifications is included in Section XI, Appendix of "Rules for Field Welding of Steel Storage Tanks."

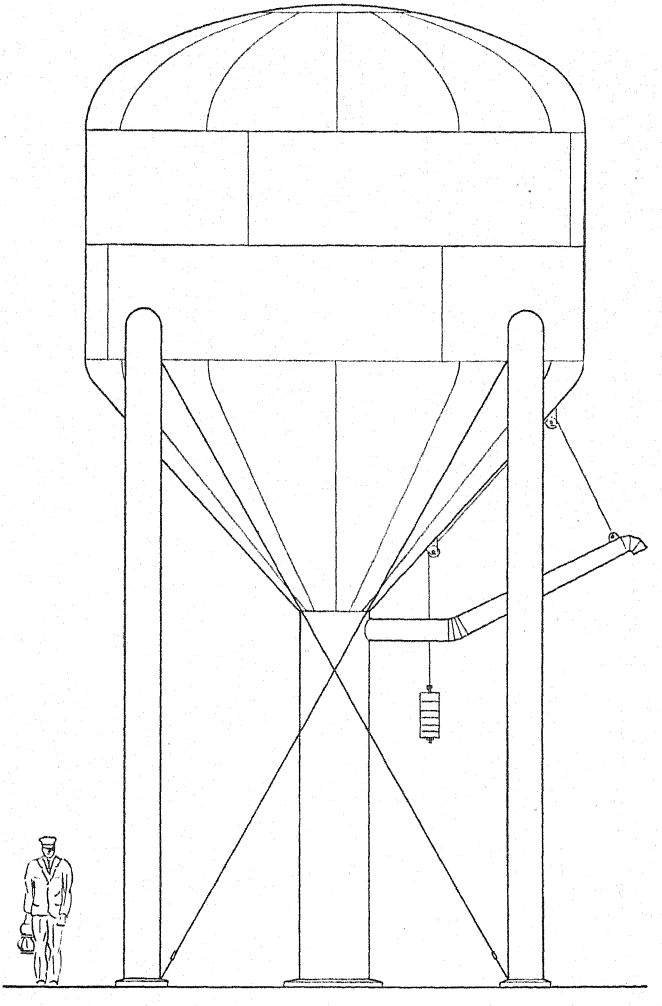


Fig. 7—Railroad Water Tank

Selection of Storage Tanks

1. Choose a size economically suited to the proposed service and to the location.

2. Check foundation requirements carefully and provide a suitable foundation, since lack of proper foundation may cause excessive settling.

3. Provide for proper accessories such as vents, drains, manholes, etc.

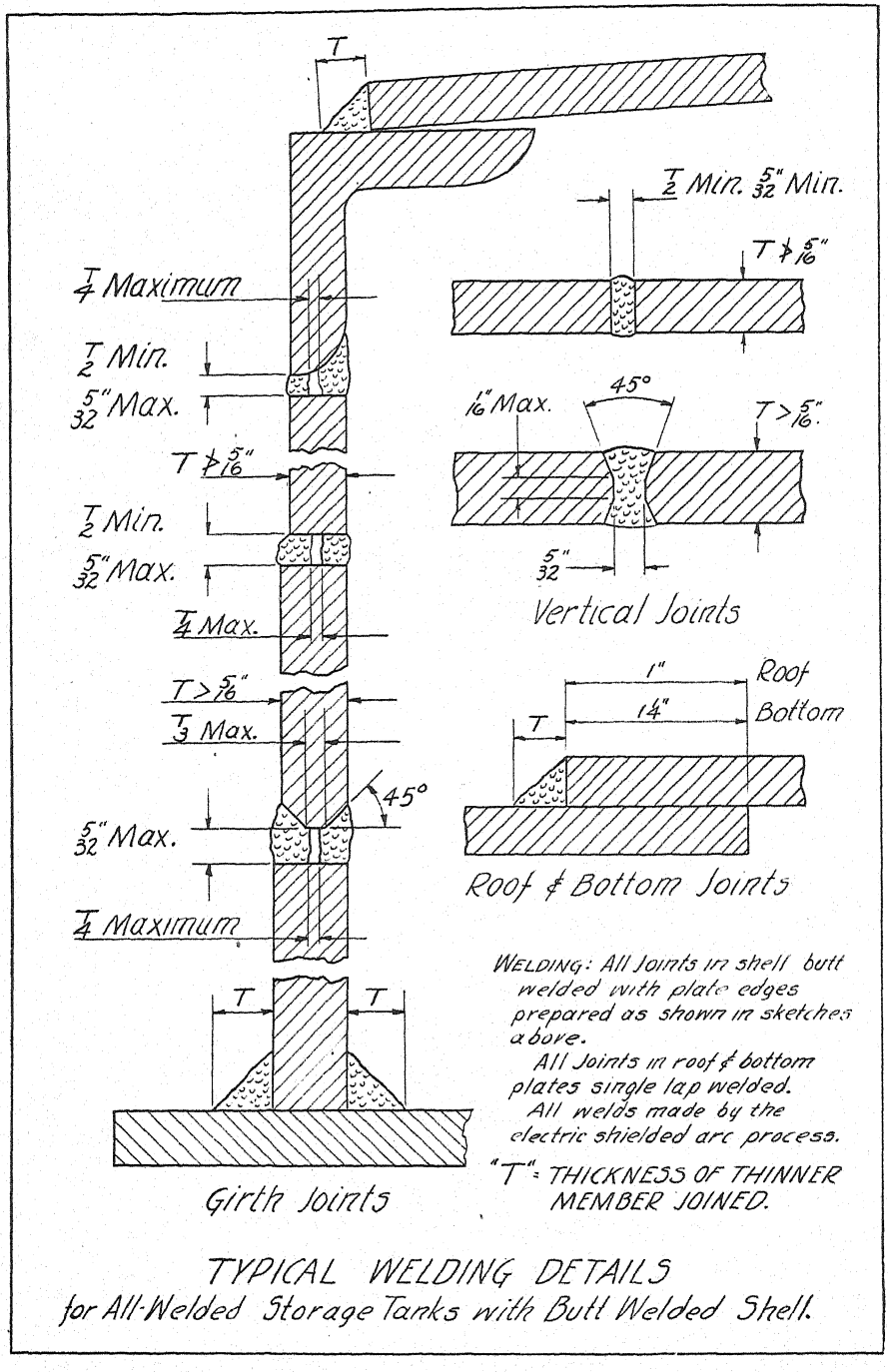


Fig. 8—Note: Single Vee Vertical Butt Joints May Also Be Used

4. Design tank according to one of the published Codes or Specifications.

5. Construct tank according to the same Code or Specification.

6. Have an experienced inspector who will intelligently check all construction details. This inspector should not be responsible to, or in the employ of, the superintendent or foreman in charge of the construction.

7. Give the inspector full authority to insist upon compliance with the Codes or Specifications.

A. W. S. RULES FOR FIELD WELDING OF STEEL STORAGE TANKS

Personnel of Committee on Rules for Field Welding of Storage Tanks: H. O. Hill Bethlehem Steel Co., *Chairman;* L. M. Dalcher, AMERICAN WELDING SOCIETY, *Secretary;* H. C. Boardman, Chicago Bridge & Iron Co.; E. W. Fowler, National Board of Fire Underwriters; L. R. Howson, Alvord, Burdick & Howson, Engineers; J. O. Jackson, Pittsburgh-Des Moines Steel Co.; A. W. Johnson, Atchison, Topeka & Santa Fe Railway; C. W. Obert, Sr., The Linde Air Products Co.; G. Raymond, Black, Sivalls & Bryson, Inc.; M. V. Reed, Wyatt Metal & Boiler Works; Walter Samans, Sun Oil Co.; H. A. Sweet, Associated Factory Mutual Fire Ins. Co.; H. T. Welty, New York Central Railroad.

I—GENERAL

1. *Scope*

a. These rules are intended to apply to the construction of fusion welded bulk storage tanks of the above-ground type for storing liquid products operating generally at atmospheric pressure or at not over 15 pounds per square inch gage pressure.*

b. The rules are intended to prescribe safe welding requirements for such tanks and apply particularly to cylindrical tanks with vertical axes and to elevated tanks, all of such diameters that they cannot be shop constructed and shipped by car or truck.

c. Two types of structures are included in these rules:

Type A

Tanks operating at atmospheric temperature and at substantially atmospheric pressure, or at a gage pressure not exceeding 27.7 inches of water, or 1 pound per square inch, in the vapor space.

e.g., Bulk storage tanks with flat bottoms, cylindrical shells and gas-tight roofs, for liquids other than water.
Standpipes, reservoirs and elevated tanks, for storage of water.

Type B

Low pressure storage tanks operating at a gage pressure, in the vapor space, not exceeding 15 pounds per square inch.

e.g., Low pressure tanks for bulk storage of liquids and vapors over same, wherein the gage vapor pressure at storage tempera-

* These rules are intended for application to vessels subject to lower pressures than those covered by the A. S. M. E. Code for Unfired Pressure Vessels.

ture, in the vapor space, is higher than 1 pound per square inch, but not exceeding 15 pounds per square inch.

d. The AMERICAN WELDING SOCIETY's Committee which prepared these rules has collaborated in the preparation of the welding features of several specifications given in Appendix XI. These specifications should be referred to for unit stresses and other applicable data when designing or constructing tanks for the particular service specified.

2. *Definitions and Symbols*

a. Welding terms employed in these rules shall be interpreted according to the definitions given in the latest edition of "Definitions of Welding Terms and Master Chart of Welding Processes," issued by the AMERICAN WELDING SOCIETY.

b. Symbols used on construction drawings shall conform to those shown in the latest edition of "Welding Symbols and Instructions for Their Use," issued by the AMERICAN WELDING SOCIETY.

II—MATERIALS

3. *Plates*

These rules cover the use of open hearth, plate materials conforming to any of the following American Society for Testing Materials Specifications of the latest revision. (In no case, however, shall the carbon content exceed 0.30%, nor the manganese content 1.00%, by ladle analysis.)

*A 7 —Steel for Bridges and Buildings.
*A10 —Mild Steel Plates.
A70 —Carbon Steel Plates for Stationary Boilers and Other Pressure Vessels.
A78 —Low Tensile Strength Carbon-Steel Plates of Structural Quality for Welding.
A89 —Low Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities (for fusion welding).
A113—Structural Steel for Locomotives and Cars (Plates for cold pressing).
A201—Carbon-Silicon Steel Plates of Ordinary Tensile Ranges for Fusion-Welded Boilers and Other Pressure Vessels.

4. *Structural*

These rules cover the use of open hearth, structural materials conforming to the following A. S. T. M. Specification of the latest revision. (The carbon content shall not exceed 0.30%, nor the manganese content 1.00%, by ladle analysis.)

A7—Steel for Bridges and Buildings.

* Steels marked are those that have been commonly used for storage tank construction.

5. *Copper Bearing Steel*

Copper bearing steel with content of about 0.20% copper may be used when specified. In other particulars the steel shall conform to specifications enumerated above.

6. *Forgings*

These rules cover the use of forgings conforming to the following A. S. T. M. Specifications of the latest revision, using open hearth steel. (In no case shall the carbon content exceed 0.30% by ladle analysis.)

a. Plate Forgings

A-78 —Low Tensile Strength Carbon-Steel Plates of Structural Quality for Welding.
A-89 —Low Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities (for fusion welding).

b. Forgings, Other Than Plate

A-235—Class *B*—Carbon-Steel Forgings for General Industrial Use.

c. Forged and Rolled Pipe Flanges

A-181—Class *I*—Forged or Rolled Steel Pipe Flanges for General Service.

7. *Castings*

These rules cover the use of castings conforming to the following A. S. T. M. Specification of the latest revision. (Carbon content not to exceed 0.25% by ladle analysis.)

A-215—Grade A-3-W—Carbon-Steel Castings Suitable for Fusion Welding for Miscellaneous Industrial Uses.

8. *Filler Metal*

a. Electrodes shall conform to the A. W. S.-A. S. T. M. Specifications for Iron and Steel Arc Welding Electrodes of the latest revision, Serial Designation A-233, using the following classifications:
E-6010, E-6011, E-6012, E-6013, E-6020 and E-6030.
The classification number selected must be suitable for the electric current characteristics and also for the position of welding.

b. Gas welding rods shall conform to the A. W. S.-A. S. T. M. A-251 Specifications for Iron and Steel Gas Welding Rods of the latest revision, using the GA-60 classification.

III—QUALIFICATION OF WELDING PROCEDURE AND TESTING OF WELDING OPERATORS

9. *Application*

Welding procedure shall be qualified and welding operators shall be tested according to the latest rules of the AMERICAN WELDING SOCIETY

"Standard Qualification Procedure," using the following values and modifying conditions:

10. *Groove Welds for Primary Stress*

(Joints subject to primary stress due to weight or pressure of tank contents.)

a. Tension Test, Reduced-Section Tension Test—not less than 95 per cent of the minimum of the specified A. S. T. M. tensile range of the base material.

b. Free Bend Test—minimum elongation 20 per cent.

c. Root, Face and Side Bend Test—Any specimen in which a crack is present after the bending, exceeding $^1/_8$ inch measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered

11. *Groove Welds for Secondary Stress*

(Joints subject to secondary stress, those not directly affected by weight or pressure of tank contents.)

a. Tension Test—Butt joints which do not require full penetration shall have the procedure qualified by the Reduced-Section Tension-Test only. This test shall not be used for the qualification of welding operators.

b. Reduced-Section Tension Test—shall give values not less than 110 per cent of the specified strength of the joint.

12. *Fillet Welds*

a. Transverse Shear Test—shall have a minimum value in pounds per square inch equal to seven-eighths ($^7/_8$) of the minimum of the specified A. S. T. M. tensile range of the base material.

b. Longitudinal Shear Test—shall have a minimum value in pounds per square inch equal to two-thirds ($^2/_3$) of the minimum of the specified A. S. T. M. tensile range of the base material.

c. Fillet Weld Soundness Test—Any specimen in which a crack is present after the bending, exceeding $^1/_8$ inch measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered.

d. Double fillet welded lap joints using various size welds, such as used to resist secondary stress, may be qualified with shear tests only, using the unit shear stress values given in Paragraphs *a* and *b*. Such tests shall not be used for the qualification of welding operators.

13. *General*

a. An operator who has been qualified for welding on plate will be permitted to perform the incidental pipe welding required in the fabrication and attachment of tank appurtenances.

b. Contractor shall submit qualification test reports for the procedure he intends to use, including all types of welded joints, welded in all

positions to be used in the construction. These test reports shall bear proper witness certification of a reputable testing laboratory or inspection agency, stating that such tests were performed in accordance with the above mentioned requirements. The tests need not be repeated provided that the procedure is not modified.

c. All welding operators assigned to weld on tanks constructed under these rules shall have been tested under the above mentioned AMERICAN WELDING SOCIETY "Standard Qualification Procedure." The contractor shall certify that such tests were performed in accordance with the above mentioned requirements.

d. The operator qualification tests herein specified shall be considered as remaining in effect indefinitely unless (1) the welding operator has not been continuously employed by the contractor on similar work, using similar welding procedure, for a period of three months or more since making qualification tests; or unless (2) there is some specific reason to question an operator's ability. In case (1) above, the requalification test need be made only in the $^3/_8$-inch thickness.

e. The contractor shall maintain a record of each welding operator employed by him, showing the dates and results of qualification tests and the work-identification mark assigned to him.

IV—WELD DESIGN VALUES

14. *Structural Joints*

Welded joints shall be proportioned so that the stresses on a section through the throat of the weld, exclusive of weld reinforcement, shall not exceed the following percentages of the allowable working tensile stress of the structural material joined.

a. *Groove Welds*

Tension	85 Per cent
Compression	100 Per cent
Shear	75 Per cent

b. *Fillet Welds**

Transverse shear	65 Per cent
Longitudinal shear	50 Per cent

15. *Tank Plate Joints*

	Type of Joint	Efficiency Per Cent
a.	Double-welded butt joint with complete penetration.	85 Tension; 100 Compression
b.	Double-welded butt joint with partial penetration and with the unwelded portion located substantially at the middle of the thinner plate.	$85\ \frac{Z}{T}$ Tension; $100\ \frac{Z}{T}$ Compression

* Stress in a fillet weld shall be considered as shear on the throat, for any direction of the applied load. The throat of a fillet weld shall be assumed as 0.707 times the length of the shorter leg of the fillet weld.

Where: Z is the total depth of penetration from the surfaces of the plate (use the thinner plate if of different thicknesses).

T is the thickness of the plate (use the thinner plate if of different thicknesses).

c.	Single-welded butt joint with suitable backing-up strip or equivalent means to insure complete penetration.	85 Tension; 100 Compression
d.	Double-welded lap joint with full-fillet weld on each edge of joint.	75 Tension or Compression
e.	Double-welded lap joint with full-fillet weld on one edge of joint and an intermittent full-fillet weld on the other edge of joint.	$75\left\{\frac{1+X}{2}\right\}$ Tension or Compression

Where: X is the percentage of full-fillet intermittent welding, expressed as a decimal.

f.	Lap joint with full-fillet welds, or smaller, on either or both edges of the joint, welds either continuous or intermittent.	$75\left\{\frac{XW_1 + YW_2}{2T}\right\}$ Tension or Compression

Where: X and Y are percentages of intermittent welds for welds W_1 and W_2, respectively, expressed as a decimal.

W_1 and W_2 are the sizes of the welds on each edge of the joint, respectively. (W_2 will be zero for a joint welded on one edge only.)

T is the thickness of plate (use the thinner plate if of different thicknesses).

V—JOINT DESIGN

16. *Butt Joints Subject to Primary Stress from Weight or Pressure of Tank Contents*

e.g., Vertical joints of cylindrical tank shells, type A tanks.
All joints below the point of support in suspended bottom, type A tanks.
All joints in low pressure, type B tanks.
(Does not apply to roofs of type A tanks subject to vapor pressure only.)

These joints may be double welded to insure complete penetration, or they may be single welded with suitable backing-up strip or equivalent means to insure complete penetration.

17 *Butt Joints Subject to Secondary Stress*

e.g., Horizontal joints of cylindrical tank shells, type *A* tanks.

These joints shall be designed to develop an efficiency of at least 57 per cent, based on the thickness of the thinner plate joined. They shall be double welded and may have partial penetration (at least two-thirds penetration required) with the unwelded portion located substantially at the middle of the thinner plate. (This joint shall be at least equivalent to two-thirds that of a double-welded butt joint with full penetration.)

18. *Lap Joints Subject to Primary Stress from Weight or Pressure of Tank Contents*

e.g., Vertical joints of cylindrical tank shells, type *A* tanks.
All joints below the point of support in suspended bottom, type *A* tanks.

All joints in low pressure, type *B* tanks.
(Does not apply to roofs of type *A* tanks subject to vapor pressure only.)

These joints shall have continuous full-fillet welds on both sides of the joint.
(Maximum thickness permitted for this type of joint—$^1/_2$ inch.)

19. *Lap Joints Subject to Secondary Stress*

e.g., Horizontal joints of cylindrical tank shells, type *A* tanks.

These joints shall be welded on both sides with continuous fillet welds. They shall be designed to develop an efficiency of at least 50 per cent, based upon the thickness of the thinner plate joined. (This joint shall be at least equivalent to two-thirds that of a double full-fillet lap joint.)
(Maximum thickness permitted for this type of joint—$^5/_8$ inch.)

20. *Flat Tank Bottoms Resting Directly on Grade or Foundation—Type A Tanks*

Bottoms shall be built to one of two alternative methods of construction:

a. *Lap joint construction*—Bottom plates need be welded on the top side only with continuous full-fillet welds on all seams.
Marginal sketch plates under the bottom ring of cylindrical shells, in the case of lap joint construction, shall have the outer end of the joint fitted and welded with groove or fillet welds to form a smooth bearing under the shell.
(Maximum thickness for lap joint bottoms shall be $^1/_2$ inch.)

b. *Butt joint construction*—These joints shall be single welded from the top side, using suitable backing-up strip or equivalent means to insure complete penetration.

21. *Shell to Bottom Joint*

(Applies to vertical cylindrical shells with flat bottoms, type *A* tanks.)

The attachment between bottom edge of the lowest course shell plate

and the bottom sketch plates shall be by a continuous fillet weld laid on both sides of the shell plate. The size of each weld shall be equal to the thickness of the sketch plate or the thickness of the shell plate, whichever is smaller, with a maximum size of $^1/_2$ inch. The sketch plates shall extend outside the tank shell a distance of at least 1 inch beyond the toe of the weld.

22. *Roof Plates*

a. Roofs not subject to hydrostatic pressure from tank contents, nor to vapor pressure greater than 3 inches of water: Such roof plates need be welded on the top side only with continuous full-fillet welds on all seams.

b. Roofs subject to hydrostatic pressure from tank contents, and/or to vapor pressure greater than 3 inches of water: Such roof plate joints shall be designed to conform to the efficiency values given in Paragraph 15.

23. *Unsymmetrical Butt Joints*

The wide faces of unsymmetrical V or U groove welds may be on the outside or the inside of the tank plating.

VI—WELDING DESIGN DETAILS

24. *Maximum Thickness of Material to Be Welded*

a. Maximum thickness permitted for lap joints subject to primary stress from weight or pressure of tank contents—$^1/_2$ inch.
e.g., Vertical joints of cylindrical tank shells, type *A* tanks.
All joints below the point of support in suspended bottom, type *A* tanks.
All joints in low pressure type *B* tanks.

b. Maximum thickness permitted for lap joints subject to secondary stress—$^5/_8$ inch.
e.g., Horizontal joints of cylindrical tank shells, type *A* tanks.

c. Maximum thickness for lap joints in flat tank bottoms resting directly on grade or foundation, type *A* tanks—$^1/_2$ inch.

d. Maximum thickness of metal permitted to be field welded—$1^1/_2$ inches.

25. *Minimum Laps for Lap Joints*

a. Joints subject to primary stress from weight or pressure of tank contents—5 *T*.
e.g., Vertical joints of cylindrical tank shells, type *A* tanks.
All joints below the point of support in suspended bottom, type *A* tanks.
All joints in low pressure, type *B* tanks.
(Does not apply to roofs of type *A* tanks subject to vapor pressure only.)

b. Joints subject to secondary stress—3 T with a minimum of 1 inch.
e.g., Horizontal joints of cylindrical tank shells, type A tanks.
Flat tank bottoms, and roofs subject to vapor pressure only, type A tanks.

Where: T is the thickness of material welded (use the thinner plate if of different thicknesses).

26. *Intermittent Welding*

a. The length of any segment of intermittent weld shall be not less than 4 times the weld size with a minimum of $1^1/_2$ inches.

b. Intermittent welding shall not be used on tank shell plating.

c. Intermittent groove welds shall not be used.

d All seams of intermittent welding shall have continuous welds at each end for a distance of at least 6 inches.

e. When a seam of intermittent welding intersects a plate joint, continuous welds shall be applied for a distance of at least 6 inches on each side of the joint.

27. *Minimum Size Fillet and Seal Welds*

a. Plates $^3/_{16}$ inch and less in thickness shall have full-fillet welds. Plates over $^3/_{16}$ inch thick shall have welds of a size not less than one-third the thickness of the thinner plate at the joint, with a minimum of $^3/_{16}$ inch.

b. Sealing, when desired, shall not be accomplished by running a bead of minimum dimension along the intervals between intermittent strength welds, but by applying a continuous weld, combining the functions of sealing and strength and changing section only gradually and as changes in the required strength may necessitate.

28. *Minimum Length of Welds*

a. The minimum length of any weld shall be four times the size, with a minimum of $1^1/_2$ inches, or else the size of the weld shall be considered not to exceed one-fourth its length.

b. The effective length of a fillet weld shall not include the length of tapered ends. A deduction of at least $^1/_4$ inch shall be made from the over-all length as an allowance for the tapered ends.

29. *Finish of Plate Edges*

a. The welding edges of plates may be universal mill edges or they may be prepared by shearing, machining, chipping or mechanically guided gas cutting, except that irregular edges may be prepared by manually guided gas cutting.

b. When edges of plates are gas cut, the resulting surface must be uniform and smooth and must be freed of slag accumulations before welding. All cutting shall follow closely the lines prescribed.

c. Shearing of material for butt joints shall be limited to $^1/_2$ inch thickness or less. Material for all permitted thicknesses of lap joints may be sheared.

30. *Joint Stagger*

Shell plate joints subject to stress from weight or pressure of tank contents shall have joints in adjacent courses staggered by at least one-fourth the distance between such joints.

VII—DETAILS OF WELDING PROCEDURE

31. *General*

All welds in the tank and structural attachments shall be made in a manner to insure complete fusion with the base metal, within the limits specified for each joint, and in strict accordance with the qualified procedure.

32. *Preparation of Welding Surfaces*

Surfaces to be welded shall be free from loose scale, slag, heavy rust, grease, paint and any other foreign material excepting tightly adherent mill scale. A light film of linseed oil or spatter film compound may be disregarded. Joint surfaces shall be smooth, uniform and free from fins, tears and other defects which adversely affect proper welding. A fine film of rust adhering after wire brushing on cut or sheared edges that are to be welded, need not be removed.

33. *Weather Conditions*

Welding shall not be done when the temperature of the base metal is less than 0°F.; when surfaces are wet from rain, snow or ice; when rain or snow is falling on the surfaces to be welded; nor during periods of high wind, unless the operator and the work are properly protected. At temperatures between 32° and 0° F., the surface within 3 inches of the point where the weld is to be started, shall be heated to a temperature warm to the hand before the welding is started.

34. *Cleaning Between Passes*

Each pass of weld metal on multi-pass welding shall be cleaned of slag and other loose deposits before applying the next pass.

35. *Tack Welds*

Erection tack welds used in the assembly of joints subject to primary stress from weight or pressure of tank contents and those used for assembling the tank shell to bottoms are to be removed ahead of the continuous welding. Tack welds used in the assembly of joints subject to secondary stress, such as those in flat bottoms, roofs and circumferential seams of cylindrical tank shells of type *A* tanks, need not be removed provided that they are sound and the cover beads are thoroughly fused into the tack welds.

36. *Peening*

a. Peening of weld layers or passes may be used to prevent undue distortion. Surface layers shall not be peened.

b. Peening shall be performed with light blows from a power hammer using a blunt-nosed tool.

37. *Weld Contour*

a. In all welds, the surface passes shall merge smoothly into each other.

b. Undercutting of base metal in plate adjoining the weld is a defect and shall be repaired, except as permitted in Paragraphs 48*f* and *g*.

c. All craters shall be filled to the full cross-section of the weld.

38. *Weld Reinforcement*

On butt joints, no part of the finished face in the area of fusion shall lie below the surface of the base plate adjoining. The weld reinforcement shall be a minimum, preferably not more than $^1/_{16}$ inch above the surface.

39. *Chipping and Gas Gouging of Welds*

The chipping at the root of welds and chipping of welds to remove defects may be performed with a round-nosed tool, or by gas gouging.

40. *Flat Tank Bottoms—Type A Tanks*

The bottom plates, after being laid out and tacked, shall be joined by welding the joints in a sequence which the contractor has found to result in the least distortion due to shrinkage of the welding, and to provide, as nearly as possible, a plane surface.

41. *Tank Shell*

a. On vertical joints, weld metal for any of the passes may be applied with either upward or downward progress of the welding, provided that the contractor shall have qualified the direction he selects fo each pass, in his procedure qualification and operator tests.

b. The shell plates shall be joined by welding the joints in a sequence which the contractor has found to result in the least distortion due to shrinkage of the welding and which will avoid kinks at the vertical joints.

42. *Matching Plates*

a. Lap joints: At all lap joints the plates shall be held in close contact during the welding operation. The separation shall be not more than $^1/_{16}$ inch. The size of the fillet weld shall be increased by the amount of the separation.

b. Butt joints:

(1) In butt joints subject to primary stress from weight or pressure of tank contents, the adjoining plates shall be accurately aligned and retained in position during the welding operation, so that in the finished joint, the center lines of adjoining plate edges shall not have an offset from each other, at any point, in excess of 10 per cent of the plate thickness (use the thickness of the thinner plate if of different thicknesses) or $^1/_{16}$ inch, whichever is larger.

(2) In butt joints subject to secondary stress, the adjoining plates shall be accurately aligned and retained in position during the welding operation, so that in the finished joint, the thinner plate (if one is thinner than the other), or either plate (if both plates are of the same thickness), shall not project beyond its adjoining plate by more than 20 per cent of the plate thickness (use the thickness of the thinner plate if of different thicknesses), with a maximum of $^1/_8$ inch.

VIII—STIPULATIONS FOR TESTING WELDED SHELL JOINTS BY SECTIONING METHODS

43. *Application*

The examination of the welded structure by sectioning methods is more satisfactory when applied to butt joints, which makes it highly desirable that the shell of the all-welded tank be constructed with butt joints throughout. While it is possible to cut sections from lap joints, it will require twice as many sections on the double-fillet-welded joints to obtain as many sections per unit length of joint as for butt joints.

44. *Sectional Specimens*

a. Sectional specimens are segments cut from the welded joints with a cylindrical cutting tool or spherical saw, which removes a portion of the plate bounding the welded joint and exposes thereon two cross sections of the weld. The segments must expose the full cross section of the welded joint.

b. Segments cut with a cylindrical tool are called trepanned plugs. Segments cut with a spherical saw are called spherical segments.

45. *Number and Location of Test Segments*

a. Sectional testing shall be confined to tank shell joints, particularly those subject to primary stress from weight or pressure of tank contents. It need not be applied to flat tank bottoms resting directly on grade or foundation, nor to the welds between flat tank bottoms and the first ring of tank shell, nor to the welds connecting top curb angle to shell and to roof, nor to a roof not subject to primary stress from weight or pressure of tank contents, nor to welds connecting manholes and other accessories.

b. Joints subject to primary stress from weight or pressure of tank contents: One segment shall be cut from the first 10 feet of completed joint welded by each operator. Thereafter, one segment shall be cut from approximately every 100 feet of joint, except that if the sum of the lengths of vertical joints in any course is less than 100 feet, one segment shall be cut from one vertical joint in each course of cylindrical tank shells, type *A* tanks. It is permissible to test two operators' work with one segment if they weld opposite sides of the same seam. When a segment of this type is rejected it must be determined whether one or both operators were at fault, by subsequent tests of the individual operator's work.

c. Joints subject to secondary stress: One segment shall be cut from approximately every 200 feet of joint, except that if the full length of a circumferential seam is less than 200 feet, one segment shall be cut from each circumferential seam of cylindrical tank shells, type *A* tanks.

d. It is to be recognized that the same welding operator may, or may not, weld both sides of the same joint. In so far as possible an equal number of segments shall be cut from the work of each operator welding on the tank, except this requirement shall not apply where

the length of joint welded by an operator is very much less than average.

e. For lap joints, two segments shall be removed at each test point, one from each fillet weld. They shall not be taken on the same center line, but shall be offset approximately three inches parallel to the axis of the joint.

f. Spherical segments shall be cut from the outside of the tank shell for butt joints and from the welded surface for lap joints.

g. The location for cutting the test segments may be determined by the purchaser's inspector.

h. Test segments shall be taken as the work progresses, as soon as practicable after all the joints accessible from one scaffold position have been welded.

46. *Size of Sectional Segments*

a. The width or diameter of the segment shall be not less than the width of the finished weld plus $^1/_8$ inch with a minimum of $^1/_2$ inch.

b. The segment shall be removed on the center of the weld in such a manner that a least $^1/_{16}$ inch of base metal will be removed with the segment on each of the two sides.

47. *Preparation of Sectional Segments*

a. Sectional segments may be etched for inspection by any of the following methods:

(1) Without requiring any finishing or other preparation, place in boiling 50 per cent solution of muriatic (hydrochloric) acid until there is a clear definition of the structure of the weld. This will require approximately one-half hour.

(2) Grind and smooth segments with emery wheel and/or emery paper and then etch by treating with a solution of one part ammonium persulphate (solid) and nine parts of water by weight. The solution should be used at room temperature and should be applied by vigorously rubbing the surface to be etched with a piece of cotton kept saturated with the solution. The etching process should be continued until there is a clear definition of the structure of the weld.

(3) Grind and smooth segments with emery wheel and/or emery paper and then etch by treating with a solution of one part of powdered iodine (solid form), two parts of powdered potassium iodide, and ten parts of water, all by weight. The solution should be used at room temperature and should be brushed on the surface to be etched until there is a clear definition of the structure of the weld.

b. To preserve the appearance of the etched segments they should, after etching, be washed in clear water, the excess water removed, then immersed in ethyl alcohol, and dried. The etched surfaces may then be preserved by coating with a thin, clear lacquer.

48. *Inspection of Sectional Segments*

a. The etched segments shall be examined to ascertain the extent of weld defects, such as gas pockets, slag inclusions, lack of fusion, undercutting and cracks.

b. For all welds, the etched surfaces of the segments shall show complete fusion between the weld metal and the base metal within the depth of the weld required for the applicable joint. There shall be no cracks in any weld.

c. For butt joints, slag inclusion is permissible where it occurs between layers of the weld, is substantially parallel to the plate surface and is equal to not more than one-half the width of the weld metal; and when it occurs across the thickness of the plate and is equal to not more than 10 per cent of the thickness of the thinner plate.

d. For lap joints, slag inclusion is permissible where it occurs between layers of the weld, is substantially parallel to the face of the weld and is equal to not more than one-half the width of the weld metal, measured in a direction parallel to the face of the weld; and when its greatest dimension measured in a direction perpendicular to the face of the weld does not exceed 10 per cent of the throat.

e. Gas pockets are permissible that do not exceed $^1/_{16}$ inch in the greatest dimension and when there are no more than six gas pockets of this maximum size per square inch of the weld metal or where the combined areas of a greater number of pockets do not exceed 0.02 sq. in. per sq. in. (2%) of weld metal.

f. For butt and lap joints subject to primary stress from weight or pressure of tank contents, there shall be complete penetration and no undercutting.

g. For butt joints subject to secondary stress, penetration is only required within the limits established by Paragraph 17. A maximum undercut of $^1/_{32}$ inch at each edge of the weld may be permitted, provided that the unwelded portion plus the undercut shall not reduce the thickness of the joint more than $^1/_3$ of the thickness of the thinner plate joined.

h. For lap joints subject to secondary stress, an undercut $^1/_{32}$ inch deep, measured along either leg, and lack of penetration at the root of $^1/_{16}$ inch, measured along either leg or the throat, shall be the maximum permitted, provided that the size of the weld be increased to compensate for the deficiency in root penetration.

i. Where a defective segment is located, additional segments shall be cut from the same operator's work 2 feet on each side of the defective segment wherever the joint length will permit. If additional defective segments are found, then more segments shall be cut at intervals of 2 feet on the same operator's work until the limit of the defective welding has been definitely established; or the contractor may proceed to replace all the welding done by that operator without cutting out additional segments.

j. Defects in welds shall be removed by chipping or by gas gouging

from one or both sides of the joint, as required, and rewelding. Only sufficient cutting out of defective joints is to be required as is necessary to correct the defects. Replacement welds in joints shall be checked by repeating the original test procedure.

49. *Method of Closing Openings from Which Segments Have Been Removed*

Subject to the stated limitations, openings may be closed by any of the following methods:

a. *Openings cut with a spherical saw:* For butt joints place a backing-up plate where necessary on the inside of the tank shell over the opening. For lap joints the base plate material opposite the weld will usually serve as a backing-up plate. Fill the opening completely with weld metal. Rebuild fillet welds where cut.

b. *Trepanned plug openings for joints subject to secondary stress only:* Insert a disk in the hole, which disk shall have a fairly close fit in the hole, and shall have a thickness at least $^1/_8$ inch less than the thickness of the thinner plate at the joint. The disk shall be inserted in a mid-position between the surfaces of the thinner plate for butt joints and in a mid-position of the continuous plate for lap joints. Both sides of the disk shall be welded over completely, fusing the circular edges of the disk into the plate material and making the surfaces of the weld substantially flush with the plate surfaces Rebuild fillet welds where cut.

c. *Trepanned plug openings for joints subject to primary or secondary stress and where the thickness of the thinner plate at the joint is not greater than $^1/_3$ the diameter of the hole:* Place a backing-up plate on the inside of the tank shell over the opening. Fill the hole completely with weld metal applied from the outside of the tank shell. Rebuild fillet welds where cut.

d. *Trepanned plug openings for joints subject to primary or secondary stress and where the thickness of the thinner plate at the joint is not less than $^1/_3$, nor greater than $^2/_3$, the diameter of the hole:* Fill the hole completely with weld metal applied from both sides of the tank shell. Rebuild fillet welds where cut.

e. *Trepanned plug openings for butt joints subject to primary or secondary stress and where the thickness of the thinner plate at the joint does not exceed $^7/_8$ inch:* Chip a groove on one side of the plate each way along the seam from the hole. The groove at the opening shall have sufficient width to provide a taper to the bottom of the hole, and the length of the groove on each side of the opening is to have a slope of 1 to 3. Using a backing-up plate on the side opposite which the chipping is done, or a thin disk (not over $^1/_8$ inch thick) at the bottom of the hole, fill the groove and the hole with weld metal.

f. *Trepanned plug openings for butt joints subject to primary or secondary stress and for plates of any thickness:* Chip a groove on both sides of the plate each way along the seam from the hole. The groove at the opening shall have sufficient width to provide a taper to the middle of the plate, and the length of the groove on each side of the opening is to have a slope of 1 to 3. Place a thin disk (not over

$^1/_8$ inch thick) in the hole at the middle of the plate and fill the grooves and the hole on both sides with weld metal.

50. *Record of Segments*

a. The segments, after removal, shall be properly stamped or tagged for identification, and, after etching, kept in proper containers with a record of their place of removal as well as of the welding operator who performed the welding. A record shall be made by the inspector of all segments, with their identification marks, on a developed shell-plate diagram.

b. After the completion of the structure, the segments may be retained by the purchaser, if he so desires, otherwise they may be discarded.

IX—TANK TESTING

51. *Testing Flat Bottoms Resting on Foundations or Grades*

After the bottom has been welded completely, including the attachment of at least the lowest shell course, oil or water, to be supplied by the purchaser, may be pumped underneath the bottom, maintaining a head of at least 6 inches of liquid, by holding that depth around the edge of the bottom, inside a temporary dam; or the joints may be tested with a suitable material such as strong soap solution or linseed oil under air pressure or vacuum; or the joints may be tested by the magnetic dust method. The bottom shall be made entirely tight to the satisfaction of the purchaser's inspector.

52. *Testing Shell and Suspended Bottom—Type A Tanks*

Upon completion of the tank, the entire tank shell and suspended bottom, if used, shall be tested by one of the following methods: (*a*) If water is available for testing, the tank shall be filled with water, and if the tank has a gas-tight roof, filled to the level of 2 inches above the capacity line. (*b*) If sufficient water to fill the tank is not available, and the liquid to be stored has a flash point higher than 100°F., the test may be made with the liquid to be stored. (*c*) If sufficient water to fill the tank is not available, and the liquid to be stored has a flash point of 100°F. or lower, a test may be made either by painting all joints on the inside with a highly penetrating oil, such as automobile spring oil, or by applying air pressure in the tank as required for roof tests in Paragraph 53, or by both methods, carefully examining the outside of the joints for leakage. (*d*) Or the joints may be tested by the magnetic dust method.

The initial filling of a tank after the satisfactory completion of such tests should be done slowly with continuous inspection of the tank during the filling period. All leaks discovered by the above tests shall be repaired as described in Paragraphs 57 to 60, inclusive.

53. *Testing Roof—Type A Tanks*

If a tank has a gas-tight roof (such as oil storage tanks), when the tank shell is tested with water in accordance with the provisions of Paragraph 52, the roof may be tested by applying an internal air pressure equivalent to 1.5

times the opening pressure of the vent valve (except that the maximum allowable test pressure is three inches of water or 0.11 pound per square inch) and applying a suitable material such as strong soap solution or linseed oil to all seams; or the joints may be tested by the magnetic dust method. Isolated pinhole leaks may be caulked mechanically, but for any indication of considerable porosity in the seam, an additional bead of weld metal may be laid over the porous section, or the porous section may be removed and rewelded.

Where no water is available, and where a tank is tested with a liquid to be stored that may give off inflammable vapors under application of heat and/or where the tank is not entirely gas free, the only safe method by which vapor pressure can be developed for testing is by pressure as generated by the thermal expansion of the gases. Repairs either by caulking or welding should be deferred until the tank is entirely gas free.

54. *Testing Low Pressure Type B Tanks*

These tanks shall be tested in accord with the design requirements. They shall preferably be filled with water and then hydraulic or air pressure applied to the extent of the test requirements. Check all seams in contact with water for leaks, and check all seams in contact with air with a suitable material such as strong soap solution or linseed oil. The joints may be tested by the magnetic dust method.

55. *Hammer Testing*

Welded joints shall not be tested by hammering.

56. *Final Test*

Before acceptance, entire tank, when filled to its capacity level with the liquid to be stored, must be tight and free from leaks.

X—REPAIRS

57. *Repairs by Peening*

No leak in a weld shall be repaired by mechanical caulking only, except pinhole leaks in roof seams not in contact with stored liquids, type *A* tanks.

58. *Tanks Under Liquid Load*

Repairs of defects discovered after tank is filled with water for test shall be made with water level at least two feet below the point being repaired, or with the tank empty, if repairs are on or near the tank bottom. No welding shall be done on any, except water tanks, unless all lines connecting thereto have been completely blanked off.

59. *Tanks Under Pressure*

No repairs shall be attempted on tanks under pressure, or while filled with any inflammable liquid or gas, in storage or for test. In such cases, it is recommended that the tank be emptied and washed out and/or steamed out, or otherwise gas-freed in a safe manner, and all lines connecting thereto blanked off, before any repairs are made.

60. *Tanks with Inflammable Contents*

After the repairs have been made, and where no water is available for final filling test, and the product (if other than water), to be stored in the tank must be used for the test, before refilling the tank, extra care in inspection of all the welded joints should be exercised, and all points of possible defects tested with penetrating oil and/or air pressure in tank, to a maximum of 3 inches of water or 0.11 pound per square inch. If, after these precautions, the tank shows leaks on being filled with any inflammable liquid or gas, no repairs shall be attempted by the manufacturer except in a manner approved in writing by purchaser's engineer and in the presence of purchaser's inspector.

XI—APPENDIX

61. The following specifications covering the design and construction of field welded storage tanks should be referred to for unit stresses and other applicable data.

a. *American Petroleum Institute*, Dallas, Texas.
Field Welded Storage Tanks for Petroleum Products, see "API Specification on All-Welded Oil Storage Tanks, No. 12-C."

b. *American Water Works Association*, 22 East 40th St., New York, N. Y.
Field Welded Elevated Water Tanks, Standpipes and Reservoirs, see "AWWA Specifications for Elevated Steel Water Storage Tanks, Standpipes and Reservoirs."

c. *Associated Factory Mutual Fire Insurance Companies*, 184 High Street, Boston, Mass.
Field Welded Gravity Water Tanks and Steel Towers, see "Specifications of the Associated Factory Mutual Fire Insurance Companies for Gravity Water Tanks and Steel Towers."

d. *National Board of Fire Underwriters*, 85 John St., New York, N. Y.
Field Welded Tanks, Gravity and Pressure, Towers, etc., see "Standards of the National Board of Fire Underwriters for the Construction and Installation of Tanks, Gravity and Pressure, Towers, etc."

e. *American Railway Engineering Association*, 59 East Van Buren Street, Chicago, Ill.
Field Welded Water Storage Tanks for Railway Service, see "Specifications of the AREA for All-Welded Steel Tanks for Railway Water Service."

WROUGHT IRON STORAGE TANKS

In the section of this chapter dealing with steel tanks the AMERICAN WELDING SOCIETY'S rules for field welding of steel storage tanks are quoted. Thus far no officially adopted rules for field welding of wrought iron storage tanks have been prepared. Practical experience has demonstrated wrought iron's suitability for tank construction and it has been used satisfactorily for handling fresh water, oil, salt water, caustic soda, animal

fats and a wide variety of other corrosive substances. Figure 9 illustrates a typical installation.

The weldability of wrought iron and welding procedure for wrought iron are discussed in Chapter 17. It is suggested that when wrought iron is specified that the following material be adopted:

Materials.—When wrought iron is specified it shall conform to the following specifications prepared by the American Society for Testing Materials:

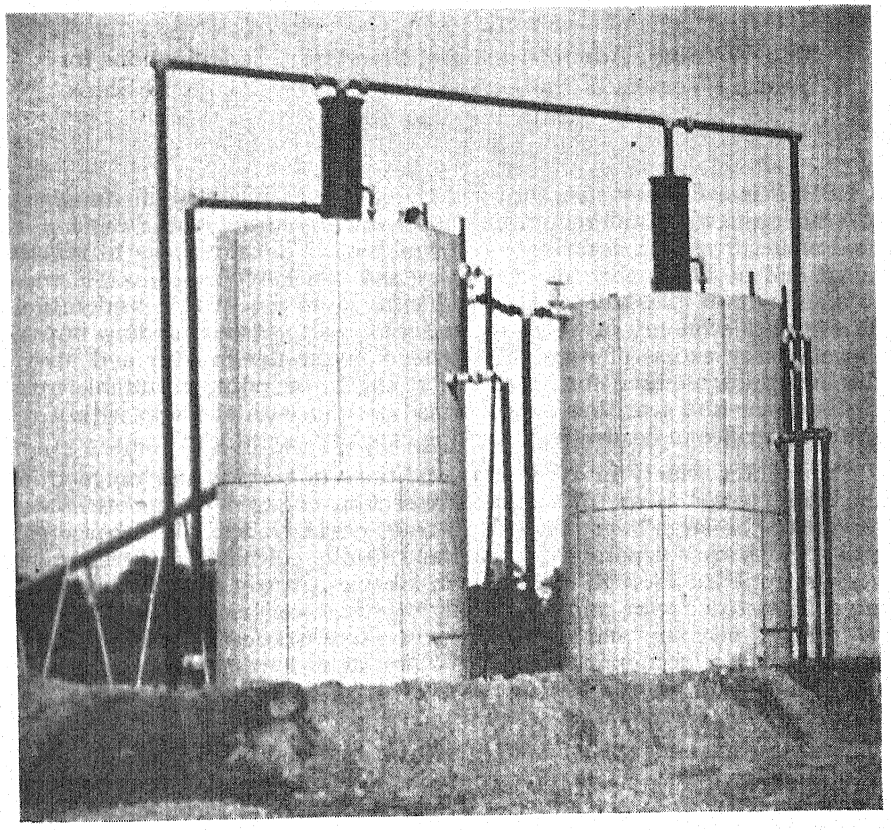


Fig. 9—Welded Wrought Iron Treating Tanks

Wrought iron plates—latest revision of A. S. T. M. Designation A-42.

Wrought iron sheets—latest revision of A. S. T. M. Designation A-162 or A-163.

Wrought iron bars, angles and shapes—latest revision of A. S. T. M. Designation A-207 or A-189.

Wrought iron pipe—latest revision of A. S. T. M. Designation A-72.

Filler metals suitable for use with wrought iron are discussed in the chapter on Welding of Carbon Irons and Steels (Chapter 17).

CHAPTER 40A

SHIPS*

Ship Welding, Administration of Standards, Specifications for Welding Vessels of the United States Navy, Merchant Ships, Ship Welding Today.

A SHIP is a floating structure and the problems involved in its design are somewhat different from those which confront the designers of land structures such as bridges and buildings. If the ship is to remain afloat and be fit for the carriage of dry and perishable cargo, water must be kept out of the hull so that tightness is an essential consideration. The utmost economy in weight of material is also of outstanding importance as any excess of material provided in the design over and above the minimum required for structural strength, including a suitable margin for wear and tear, has to be carried around with the ship with a resultant sacrifice in deadweight carrying capacity, speed, etc.

Ships differ widely in type and conditions of service and range from the small towed barge of simple box section engaged in smooth water service to the large liner operated in trans-ocean trades. In a barge the hull stresses are comparatively small and readily calculable. Ocean-going vessels propelled through the water in all conditions of wind and weather are subject to hogging and sagging in waves as well as to stresses caused by rolling, pitching and slamming which are statically indeterminate. The problem of economic structural design of such vessels is not quite so simple and their scantlings have been evolved largely on the basis of experience with due regard to scientific methods of analysis and evaluation.

Since the introduction of mild steel as a material of construction, hull scantlings have been gradually reduced. Economy in weight of material has been achieved by a gradual simplification of design through the elimination of parts which were more or less redundant and by a more scientific distribution of material. The riveted ship had reached that stage of structural development where it was becoming difficult to conceive of any major reductions to the principal scantlings without sacrificing some of that margin for wear and tear which is so essential for the life and general serviceability of a merchant vessel.

While major failures in the modern ship structure are almost unknown

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* Prepared by a committee consisting of David Arnott, American Bureau of Shipping, *Chairman;* C. W. Bryan, Jr., Federal Shipbuilding & Dry Dock Co.; A. G. Leigh, Ingalls Shipbuilding Corp.; T. M. Jackson, Sun Shipbuilding & Dry Dock Co.; H. W. Pierce, New York Shipbuilding Corp.; A. G. Bissell, Bureau of Ships, Navy Dept.

except, of course, as a result of a serious casualty, ships are not altogether free from service troubles Under stress of weather or as a result of bumping, etc., rivets may slacken and caulked seams may spring. An accumulation of even minor leaks from such cases may result in damage to perishable cargoes or in oil contamination in the case of tankers. The hull structure of gasoline tankers is particularly subject to corrosion, the wastage after some years of service being such in some cases as to require wholesale renewals of plating and rivets. In a riveted ship most of the defects which arise in service are incidental to the method used for joining the component parts of the structure.

SHIP WELDING

The growth of ship welding in the United States especially during the last decade has been remarkable. In 1929, among the vessels building to class with the American Bureau of Shipping only one small oil barge, 100 ft. long, fittingly named the *Pioneer* was of welded construction. On October 1, 1941, there were 1009 ships building or contracted for to American Bureau classification. Of these ships 298 were under 300 ft. long and were completely welded except one small survey vessel. Of the 711 larger ocean-going ships, no fewer than 207 were completely welded and in the remaining 504 ships welding was used very extensively. In short, 50% of all the merchant ships building at present in the U. S. are being completely welded.

Arc welding was at first confined to the smaller types of vessels, mostly oil tank barges, and the most noteworthy step in advance was made by the Sun Shipbuilding Company when they built in 1938 the large ocean-going tanker *J. W. Van Dyke* for the Atlantic Refining Company. The policy of the Maritime Commission in permitting builders to use welding at their discretion for all parts of the hull structure has encouraged the adoption of welding for the construction of large ocean-going ships. The defense program has tremendously accelerated ship welding, our new shipyards all having been designed and laid out primarily with a view to mass production of welded ships. It is anticipated that some of these yards when in full production will deliver a cargo ship per week, and the defense program would not have been so far ahead today if it had not been for the general adoption of ship welding.

Hull weights are materially reduced by welding the steel structure. Increased efficiency is brought about through this saving in weight and the use of high temperature, high pressure steam propelling machinery where the piping and boiler drums are invariably of welded construction as are also a great many of other machinery parts.

The saving in weight in a recently built welded tanker as compared with an earlier riveted ship of the same dimensions and of about 15,000 tons deadweight was stated to be about 1000 tons in 6000 tons or $16^{2}/_{3}\%$. Of this reduction 800 tons or $13^{1}/_{3}\%$ saving in hull weight was attributed to the use of welding, and the balance of 200 tons to the use of improved machinery. In other words there was made available an increase of $6^{2}/_{3}\%$ in deadweight carrying capacity or an increase of $5^{1}/_{3}\%$ due to the use of welding alone.

In addition to original savings in cost, to economy in fuel operation and to increase in deadweight carrying capacity there is a further saving, that of maintenance expense. In some instances this reduction in hull maintenance costs is claimed to amount to 25%.

Designing for Welding

If the maximum economies are to be achieved by the use of welding, the ship structure must be designed for welding to the exclusion of preconceived ideas based on the limitations of riveting practice. Rivet holes, faying flanges, caulking and to a large extent the fitting of brackets, gusset plates and clip connections are incidental to riveted construction and can be eliminated in welded designs. Different methods of design, fabrication and assembly, must be used in welded construction if the best and most economical results are to be obtained. Just as riveting schedules are now prepared in the drawing office so also should the schedule of welding operations show the manner of making the various joints, the types of electrodes, the number of passes or runs, etc. All of this assumes a knowledge of welding technique on the part of the draftsmen who should make themselves familiar with the fundamental principles underlying welding design. All the factors which govern the welding operation should be standardized in the interests of economy and efficiency and full control over the welding procedure should be systematically planned before hand. Properly designed welded joints have certain advantages over riveted joints. The stresses are better distributed across the section of the plate and it is possible to utilize the strength of each structural member to a much greater extent. The structure should be designed with the least number of component parts and with the minimum number of joints.

Planning the Work

The entire method of fabricating and assembling the component parts of the structure should be planned in detail before work is commenced if contraction, buckling, distortion, etc., are to be kept within reasonable limits. It is fundamental that as much as possible of the welding be done under cover, leaving a minimum amount of welding to be done on the ways. Downhand welding is less fatiguing to the operator, is cheaper and likely to produce the most efficient welds under ordinary conditions. Welding in the other positions, especially overhead, should be avoided as far as possible. Appliances for the handling of large preconstructed units are essential. Tilting tables and other suitable equipment should be provided so that the maximum amount of welding can be done on the flat. Good welding cannot be done by an operator in a cramped position so that welds should be arranged for easy accessibility. Prefabricated units should be as large as is consistent with the handling facilities and the layout of the particular yard. The amount of welding and the size of welds should be strictly governed by the minimum requirements laid down in the Rules of the American Bureau of Shipping or the U. S. Navy specifications as the case may be.

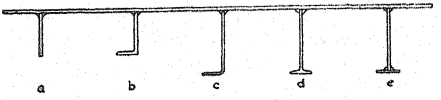
Shrinkage, Distortion, Residual Stresses

For joining the strength members of a ship structure nothing but high quality welds should be considered and this means the use of skilled operators working with the best available tools under intelligent supervision. With modern equipment including the use of high grade covered electrodes and with complete control of the welding process there can be no longer any excuse for poor welds. Assuming that the welds are first class, i.e., that the deposited metal has physical characteristics comparable to the base metal including a high degree of ductility, is uniform in quality, is free from inclusions or porosity, has good penetration and root fusion with no undercutting or overlapping along the edges of deposit, there are still difficulties associated with the practical application of the welding process which even the keenest advocates of welding cannot ignore. These are shrinkage, distortion and residual stresses. Unless suitable margins are allowed over mold loft dimensions and corrections made for contraction as construction proceeds, the completed ship will be shorter and narrower than the corresponding designed dimensions and the ends of the ship and even the bilges will tend to rise from the blocks. Distortion as evidenced by buckled plating and warping of stiffeners is also a serious problem since corrective measures are usually very costly, especially with light construction. Much can be done to minimize distortion by suitable design and welding procedure or by practical methods developed from past experience such as prespringing, etc. Weld failures on account of stresses which remain in the joint after welding do sometimes occur during construction, although such failures can usually be attributed to a wrong welding sequence and sometimes to the wrong location of welds. The problem of residual stresses should not be lightly dismissed even though experience based on full scale tests to destruction, also service tests of welded vessels, would appear to show that these locked up stresses are not any more serious than the residual rolling stresses in heavy rolled beams or in wide flanged beams. In any case, the use of high grade covered electrodes, depositing ductile filler metal together with the correct welding sequence and procedure will tend to keep these difficulties within reasonable limits.

Framing

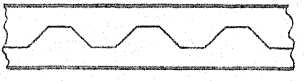
A ship structure is a combination of plates joined together by either rivets or welds to form the outside shell and decks, and framed or stiffened by plate floors, webs and rolled shapes running across and around the ship as in the transverse system of construction or in the direction of the ship's length as in the longitudinal system. Modern ships are built either on the transverse system, the longitudinal system or a combination of both. Transverse and longitudinal bulkheads while primarily fitted for subdivision purposes or to form the boundaries of tanks as in bulk oil carriers are extremely valuable contributions to the structural strength of the ship providing as they do resistance against racking and change of shape. Bulkheads are built of plates with the stiffeners either disposed vertically or horizontally although in some cases the bulkheads are formed of dished or corrugated plates to the exclusion of stiffeners. In the absence of rolled

shapes suitable for welding, shipbuilders are forced to use or adapt shapes originally designed for riveting, i.e., angles, channels and bulb angles, and such makeshifts do not make for the maximum economy in construction even where modern flame cutting equipment is available in the shipyard. Examples of welded framing in general use are as shown.



(*a*) The flat bar has obviously a very limited use and is confined to small craft.

(*b*) The inverted angle is the most common application. These are cut from channels where the required depth is outside the range of angles ordinarily rolled and in some cases are serrated for maximum economy of material as shown.



(*c*) Flanged plates used in lieu of inverted angles.

(*d*) Tee bars cut from I beams and sometimes serrated as shown for channels.

(*e*) Built up section consisting of face plate welded to web plate.

For welding purposes shapes need not be symmetrical as for riveting and a wide range in dimensions and thickness of rolled bulb plates and tee bars properly proportioned such as



if made available by our steel manufacturers would be a welcome contribution to the economics of ship welding.

Steel

The steel commonly used for hull construction comes under A.S.T.M. A131–39. The usual analysis of this specification is:

	Rimming Steel		Semi-Killed or Killed	
	Up to $^3/_4$ In.	$^3/_4$ In. to $1^1/_2$ In.	Up to $^3/_4$ In.	$^3/_4$ In. to $1^1/_2$ In.
Carbon	0.18 to 0.28	0.22 to 0.28	0.15 to 0.19	0.16 to 0.22
Manganese	0.30 to 0.60	0.30 to 0.60	0.45 to 0.60	0.45 to 0.60

ADMINISTRATION OF STANDARDS

Ship welding could not have achieved the signal success that it has reached today but for the cooperation of classification societies such as the American Bureau of Shipping whose construction rules constitute the standard for merchant shipbuilding in the various maritime countries. That welded ships have not been penalized in the matter of insurance rates as compared with riveted ships shows the confidence of the underwriting fraternity in the classification certificates granted to these vessels. It is essential that caution be exercised in the approval of any new process if only in view of the moral responsibility involved in such acceptance.

The Navy Department has carried out useful pioneer and research work which has done much to encourage the art of welding in Naval vessels. As a matter of fact, Naval work is largely responsible for the fact that so many trained and experienced welding operators are available in our shipyards today. It should be emphasized that in Naval design the utmost economy in weight of material is of vital importance with the result that the structure of the Navy ship is more complicated, more costly and relatively stronger weight for weight than that of the ordinary merchant ship.

The balance of this Chapter will deal largely with the general rules governing

I—Naval Vessels (as promulgated by the U. S. Navy) and

II—Merchant Vessels (as promulgated by the American Bureau of Shipping).

SPECIFICATIONS FOR WELDING VESSELS OF THE UNITED STATES NAVY

The Navy has issued a booklet, entitled "General Specifications—Appendix 5, Specifications for Welding." Part I covers the general requirements for welding for the Bureau of Ships, Navy Department. In addition to this appendix of the General Specifications for Building Vessels of the United States Navy, the material bureaus are developing a general departmental specification for welding in the form of sections of Appendix VII, Welding, of the General Specifications for Inspection of Material. Separate sections have been and will be issued as developed.

The scope of Appendix 5 covers all welding done for the Bureau of Ships by contractors, navy yards, naval stations and forces afloat. It gives specific information in regard to the more usual combinations of base metals and the metal arc electrodes or gas welding rods to be used in joining them.

The Welding Nomenclature and Definitions and Welding Symbols specified in the Design Section are in most respects identical with those of the AMERICAN WELDING SOCIETY.

Details of Design*

Vessels shall be so designed and constructed that the welding and riveting employed thereon shall function independently of each other. Com-

* Reproduced from Navy Specifications.

posite joints shall not be used without the specific approval of the Supervisor of Shipbuilding.

Strength members which are subjected to high tensile stresses and dynamic loading shall be so designed that when loaded in tension, dependence is not placed on the strength of the base metal normal to its plane of rolling. Where the avoidance of the foregoing is impracticable, sufficient through connections shall be provided to minimize the possibility of failure. The great majority of welded connections in the ships' structure are loaded primarily in shear and do not require special precautions; however, the lack of tensile strength of steel normal to its plane of rolling should always be borne in mind in the design of any welded structure.

Welded longitudinal joints shall not be used to connect members, either of which contain riveted transverse butt joints, except as indicated on the contract plans or as specifically approved by the Bureau.

Butts of shapes entering into the longitudinal strength of vessels may be butt-welded, where the flanges or webs of these shapes are riveted or intermittently welded to associated members, and where these members are riveted to each other, provided the welded butts of the shapes are shifted well clear of the riveted butts of associated members.

Where the welding of the butts and seams of plating is required, butt welds shall be used, except in special cases shown on contract plans or approved by the Bureau.

Welded collars shall be substituted for riveted stapling.

Plug or slot welds shall not be used when it is possible to use any other type of weld. However, slot welds are preferable to plug welds.

Oil or water stops may be of the welded type, viz.: 45° single-V groove welds, with root openings of not less than $^5/_{16}$ in. In welded construction when stops other than the welded type are used, the material or installation of the stops shall be such that they are not damaged by the welding.

The peripheries of water-tight and oil-tight floors, longitudinals, bulkheads and decks shall be welded with double continuous fillet welds, or groove T welds, depending upon the thickness of the plating.

Boundary connections of plating 6 lb. per sq. ft. or less in weight shall not be welded directly to deck or shell plating, but may be welded to a margin plate of not less than 7 lb. per sq. ft. in weight.

Fillet welds shall be extended around the ends of members to form a "U," wherever possible.

Intermittent Welds

Chain or staggered intermittent welds as shown in Fig. 1 shall not be used except in those locations where the minimum size of continuous fillet weld obtainable results in an efficiency greater than that required in section dealing with efficiency of welded joints and provided the perpendicularity of the web section being attached is maintained.

Intermittent welding shall not be used, without the specific approval of the Bureau, in the following locations:

(*a*) In locations exposed to weather.

(*b*) All tanks and voids where galvanizing is used to retard corrosion.

DESIGN DATA FOR TEE JOINTS

IMPORTANT - NOTES APPLY ONLY TO ILLUSTRATIONS ON WHICH REFERENCED.

NOTE 1- WHERE THE CLEARANCE BETWEEN MEMBERS TO BE JOINED "A" IS GREATER THAN 1/16" THE SIZE OF FILLET WELD SHALL BE THE SIZE SPECIFIED PLUS THE CLEARANCE.

NOTE 2- DIMENSION "T" IS PLATE THICKNESS TO WHICH NORMALLY APPLICABLE. IF DESIRED, PLATE THICKNESS MAY BE GREATER FOR JOINTS INDICATED.

NOTE 3- THE MINIMUM LENGTH OF AN INCREMENT SHALL BE 4 TIMES THE SIZE OF THE WELD, BUT IN NO CASE LESS THAN 1 INCH.

NOTE 4- THE MAXIMUM LENGTH OF AN INCREMENT SHALL BE 16 TIMES THE THICKNESS OF THE THINNER MEMBER, BUT IN NO CASE SHALL THIS MAXIMUM EXCEED 6 INCHES.

NOTE 5- THE MAXIMUM CENTER TO CENTER SPACING BETWEEN INCREMENTS SHALL BE 16 TIMES THE THICKNESS OF THE THINNER MEMBER, BUT IN NO CASE SHALL THIS MAXIMUM EXCEED 12 INCHES.

NOTE 6- THE MAXIMUM CENTER TO CENTER SPACING BETWEEN INCREMENTS ON THE SAME SIDE OF THE JOINT SHALL BE 32 TIMES THE THICKNESS OF THE THINNER MEMBER, BUT IN NO CASE SHALL THIS SPACING BETWEEN ADJACENT INCREMENTS ON OPPOSITE SIDES OF THE MEMBER EXCEED 12 INCHES.

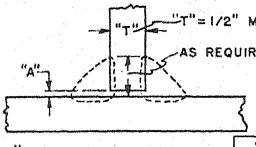
NOTE 7- THIS JOINT SHALL NOT BE USED WHEN ROOT OF WELD IS SUBJECT TO TENSION BENDING.

NOTE 8- WHEN THIS JOINT IS USED NO OBSTRUCTION SHALL BE CLOSER THAN 18 INCHES TO THE EDGE OF THE BEVELED PLATE.

NOTE 9- ROOT OF WELD SHALL BE CHIPPED OUT TO SOUND METAL BEFORE OPPOSITE SIDE OF JOINT IS WELDED.

T-1. DOUBLE FILLET WELDED TEE JOINT.

(SEE NOTES 1 & 2)

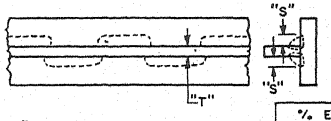


"A" = 0" TO 1/8" FOR STRAIGHT SURFACES.
"A" = 0" TO 3/16" FOR CURVED SURFACES.

% EFF.
SEE FIG.#2

T-3. STAGGERED INTERMITTENT WELDED TEE JOINT.

(SEE NOTES 2, 3, 4 & 6)

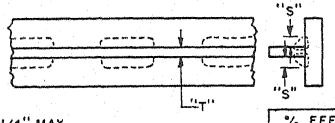


"T" = 1/4" MAX.
"S" = "T" MAX.

% EFF.
SEE FIG.#3

T-2. CHAIN INTERMITTENT WELDED TEE JOINT.

(SEE NOTES 2, 3, 4 & 5)

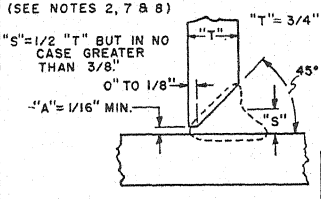


"T" = 1/4" MAX
"S" = "T" MAX.

% EFF.
SEE FIG.#3

T-12. SINGLE BEVEL TEE JOINT, WELDED ONE SIDE FILLET REINFORCED.

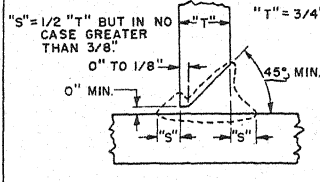
(SEE NOTES 2, 7 & 8)



% EFF.	
M.S.	H.T.S.
85	85

T-14. SINGLE BEVEL TEE JOINT, WELDED BOTH SIDES, FILLET REINFORCED.

(SEE NOTES 2, 8 & 9)



% EFF.	
M.S.	H.T.S.
100	100

Fig. 1

(*c*) For the connections of longitudinal and transverse framing to shell plating below the designed waterline in the forward one-fifth length.

The sizes and lengths of intermittent fillet welds shall be determined from the strengths of fillet welds set forth in Fig. 3 so as to give the required efficiencies. The spacing of the increments of the welds shall be such that the requirements set forth in Fig. 1 are not violated.

The length of intermittent fillet welds called for on drawings shall be considered to be the length exclusive of beginnings and craters, that is, the length of the correctly proportioned fillet.

Members welded with intermittent fillet welds shall have continuous welding on both sides for one-third of their length (but not less than 10 in. nor more than one frame space) at the ends. The increment lengths of intermittent welding called for on the drawing shall be laid off inside of these end welds.

The Design and Efficiencies of Welded Joints gives a list of items together with their connections which are welded in the construction of Naval vessels with the joint efficiencies that are required (see Figs. 1 to 3).

Welding Procedure

General.—The actual welding of ships or structures and of all parts entering into their construction shall be done in such a manner that the magnitude and extent of residual or locked-up stresses in the welds and structural members will be reduced to a minimum.

In order to expedite construction, it is considered desirable to divide the ship's hull into sections so that welding may progress outward from several centers of welding at approximately the same time.

Before any welding is begun on any particular section of the ship, structure or assembly thereof, the contractor shall submit a general welding procedure for the approval of the Supervisor of Shipbuilding. Detailed welding procedures may be required for all work, and will be required on weldments of major structural importance, such as turret assemblies, stern posts, stern frames, rudders, shaft struts, rudder crossheads, etc. Where preheat and postheat treatments are to be used, the procedure shall include the complete treatment to be followed. After approval has been obtained, the procedure shall not be departed from without approval of the Supervisor of Shipbuilding. Copies of approved procedures and alterations thereto shall be forwarded to the Bureau.

Butt welds shall be made before both members of the joint are riveted or permanently welded in place. Where, in special cases approved by the Supervisor of Shipbuilding, circumstances make it impracticable to comply with the above requirement, an unstrapped butt, which is not free to move, may be welded, provided its members are unsecured on either side of the joint for a distance of not less than 12 in. and are bowed sufficiently to allow for shrinkage. Preheating and peening should be used as necessary to minimize residual stresses and shrinkage. The above requirement is not intended to prohibit welding of the frame which acts as a backing structure in groove welds prior to making these groove welds.

Riveting occurring within the area affected by the heat of welding shall be done after the welding is completed, except:

(*a*) Riveting strips may be driven prior to welding.
(*b*) Where otherwise specifically approved by the Bureau.

Precaution shall be taken to avoid distortion or buckling of plating due to shrinkage in parts attached thereto. This may be accomplished by bolting, tack welding, rib-bands or by other approved means.

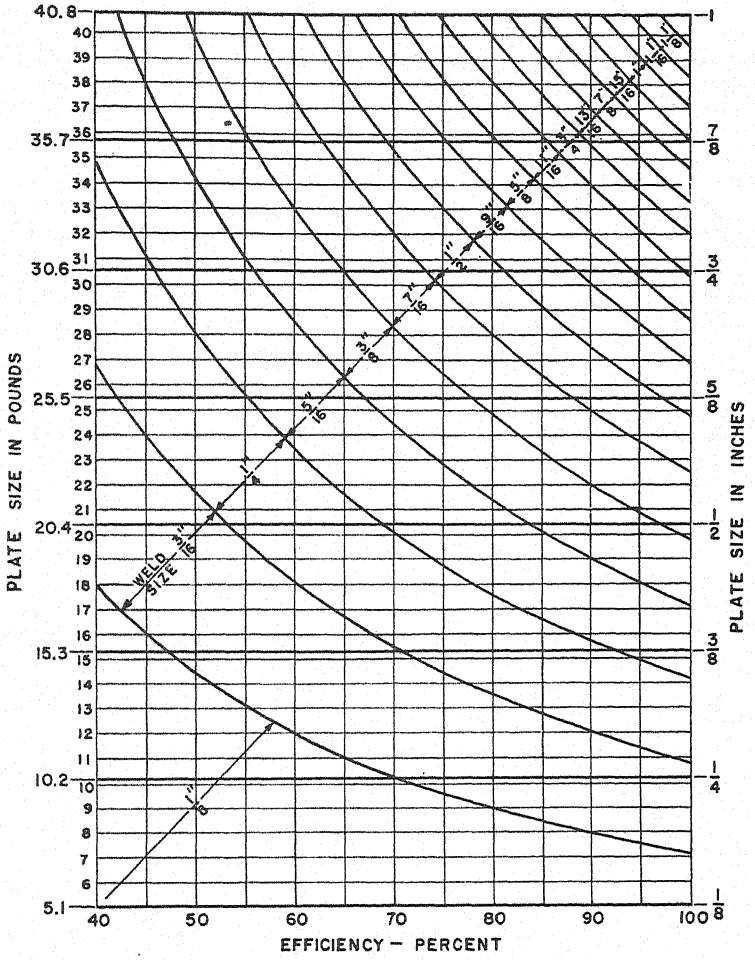


Fig. 2—Efficiencies of Welded T Joints

1. This figure for use only with Type T-1 welds shown in Fig. 1 for medium steel welded to medium or high tensile steels with electrodes as set forth in the specifications.

2. The plate size to be used in entering this figure is that of the thinner member being joined except that where one member of the joint is made of high tensile steel, the plate size shall be that of the medium steel member if it has the lesser total strength. Otherwise the size of the fillet weld shall be as set forth in the specifications for high tensile steel.

3. The weld sizes set forth in this figure have been calculated from the strength of fillet welds shown in Fig. 3 and the minimum tensile strength of medium steel (60,000) psi.

Continuous lines of welding shall be made by the back-step, cascade, wandering, block or other approved sequence in order to reduce local heating and resultant warping.

Welding shall progress symmetrically so that the shrinkage on both sides of the structure will be equalized.

Intersecting systems of framing and stiffeners shall be welded to each other before they are welded to the plating. Such welding may be completed before the plating is applied, or may be done as the intersecting joints are reached in the course of attaching the framing to the plating but before the welding of the latter is carried beyond the intersection.

Seam welds shall not be carried beyond an unwelded butt or butt lap joint until the latter has been welded.

Welds joining continuous longitudinal members to plating shall not be carried beyond an unwelded butt or butt lap joint until the latter has been welded, except in special cases approved by the Supervisor of Shipbuilding.

Collars, which are lapped on the cut member, shall be welded to the through member before they are attached to the cut member, except in special cases approved by the Supervisor of Shipbuilding. Where collars are to be butt-welded to the cut member, the butt weld shall be made prior to welding the collar to the through member.

Every effort shall be made to hold the departure of the vessel from the molded form within the following limits:

(*a*) Plus or minus $1/2$ in. from the vertical longitudinal center plane.
(*b*) One inch in 100 ft. from the designed length.
(*c*) Plus or minus 1 in. from its molded beam.
(*d*) Plus or minus $1/2$ in. vertically from the base line offsets.

In order to insure adherence to the above requirements it may be necessary to provide extra length and width on certain plates to allow for shrinkage. Check measurements shall also be made at frequent intervals throughout the construction of the vessel and corrective measures taken as necessary.

Atmospheric Conditions.—No tack or production welding of any kind shall be done when the atmospheric temperature in which the welding is to be performed is less than 10°F., nor shall any welding be done when rain or snow is falling on the surfaces being welded. The welding of butt joints in important longitudinal strength members shall not be accomplished without local preheat of 150°F. when the atmospheric temperature is below 30°F.

Condition of Surfaces.—Surfaces to be welded shall be free from rust, scale, water, oil, dirt, paint and other harmful matter, except that after pickling paint, Navy formula No. 48, need not be removed. These surfaces shall be thoroughly dried before and maintained dry during the welding operation.

Slag adhering to flame-cut edges shall be removed prior to welding these edges.

Joint Preparation.—When structures are bolted or tacked ready for welding, clearances not to exceed $1/32$ in. will be permitted between the faying surfaces of lap joints and of butt joints landing on straps or backing structure.

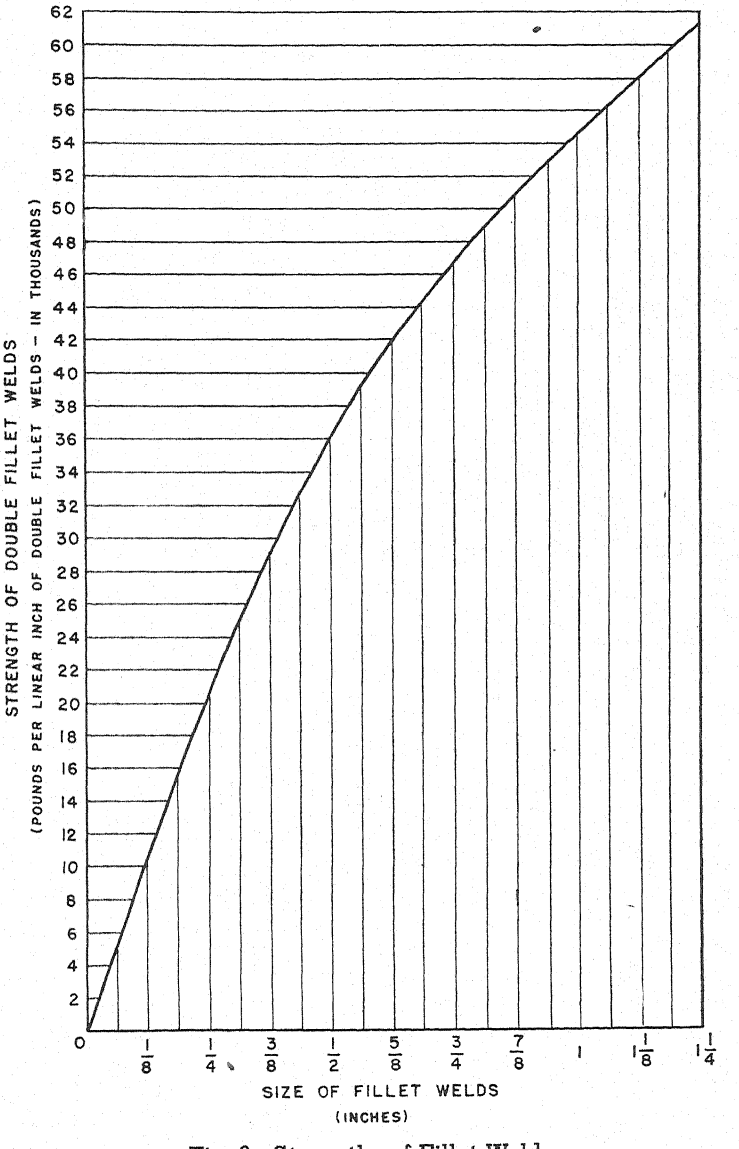


Fig. 3—Strengths of Fillet Welds

1. This figure for use only with Types T-1, T-2 and T-3 welds shown in Fig. 1 for medium and high tensile steels welded to medium or high tensile steels with electrodes as set forth in the specifications.
2. The strength of fillet welds set forth in this figure shall be used as the ultimate design strength regardless of the direction of loading.

In order to avoid cracking of fillet welds, when welding "Double Fillet Welded Tee Joints," type T-1 shown in Fig. 1, metal-to-metal contact of the members being joined shall be avoided; when welding members of heavy section, a clearance between the members being joined, of not less than $^1/_{32}$ in., shall be maintained prior to welding. This may be accomplished by means of wires or by rough machining the abutting surface.

Temporary welded attachments for erection purposes shall be kept to a minimum and shall be removed after they have served their purpose.

Tack Welding.—Tack welds shall be made with the same grade of electrode as the final weld, shall be of equal quality and shall be deposited in such a manner as to facilitate incorporation in the weld. Cracked or broken tack welds and those of poor quality shall be chipped out and all others thoroughly cleaned before the final weld is made.

Tack welds shall not be made with electrodes larger than $^1/_8$ in. diameter, except that, in tacking heavy sections, $^5/_{32}$-in. diameter electrodes may be used.

Tack welds shall be as small as can be made consistently with electrodes of the size being used, shall be not more than 1 in. long and shall be spaced only as closely as necessary to hold the joint in proper alignment.

Preheat and Postheat Treatments

Preheat Treatment.—In order to prevent cracking of the weld metal when welding heavy sections, constrained assemblies or base metals which, under normal atmospheric conditions, are subject to excessive hardening because of the welds, local preheating of the base metal to at least 150°F. shall be done.

Heavy weldments such as turret assemblies, stern frames, struts and weldments composed of members of unequal thickness shall be welded in an enclosure where the weldment can soak until it has attained a temperature of at least 60°F. before any welding is commenced, and where a similar temperature can be maintained without any interruption, until all welding is completed. The welding need not be performed continuously, provided sufficient weld metal has been deposited at the root of the weld to prevent cracking, and suitable means, such as gas burners, etc., are provided to keep the joint or joints being welded at a temperature of at least 150°F. during the interim between welding.

Postheat Treatment.—In order to place weldments in the best condition for service, general stress-relief heat treatment shall be done:

(*a*) To relieve stresses that may exist in weldments due to unequal shrinkage.
(*b*) To insure freedom from movement during and after machining.

General stress-relief heat treatment shall be accomplished on the following weldments:

(*a*) Stern posts and stern frames.
(*b*) Shaft struts.
(*c*) Propeller shaft bearings.
(*d*) Rudder cross heads.

(*e*) Turret roller paths.

(*f*) Rotating turret structure.

(*g*) Gun girders.

(*h*) Rudders and rudder support assemblies, when framing is $^1/_2$ in. thick and over, or when the assembly includes material requiring stress-relief heat treatment after welding.

(*i*) Pressure vessels, other than submarine pressure hulls or structural tanks, operating at pressures greater than 100 psi.

(*j*) Any other weldment which, in the opinion of the Bureau or Supervisor of Shipbuilding, requires stress-relief heat treatment for either of the above reasons.

This section gives rules for operation of a stress-relieving furnace and for treating special steels.

Making of Welds.—Electrodes of core diameters greater than those listed in the specifications, as suitable for welding in the various positions shall not be used.

Electrodes of core diameters greater than $^1/_4$ in. shall not be used for depositing the root passes of groove and fillet welds.

Welds may be built up by beading or weaving. When weaving is used, the passes shall not be less than twice the nominal size of the electrode. In order to obtain the maximum ductility of the weld metal, weaving shall be used, wherever practicable.

A groove weld which is to be welded from both sides shall have the root of the weld chipped out to sound metal after sufficient weld metal has been deposited on one side of the joint and before any welding is done on the opposite side of the joint. A round nose tool having a radius of not less than $^1/_8$ in. shall be used for such chipping.

Vertical welds shall be made upward, except that on plating 7.5 lb. per sq. ft. and lighter, welds may be made downward.

Undercut welds will not be accepted. If such a condition occurs, it may be corrected by depositing a small bead at the toe of the weld; however, in correcting this condition the convexity and reinforcement requirements specified shall not be violated.

Overlapping or rolling of fillet welds will not be permitted. If such a condition obtains, it shall be corrected by cutting out the unsatisfactory weld and rewelding.

The size and shape of fillet welds and the amount of reinforcement of groove welds shall be checked by a gage. Convexity and concavity of fillet welds shall not be greater than that permitted by this gage. Excessive convexity may be corrected by chipping. Excessive concavity may be corrected by depositing additional weld metal.

Fillet welds up to and including $^3/_8$ in. size shall not vary from the specified size by more than one size and then only for a total distance not greater than $^1/_4$ the length of the joint, and for not more than 6 inches continuously at any point. Fillet welds, $^7/_{16}$ in. size and larger, shall be held within the gage limits for their respective sizes.

Where groove welds occur in deck plating on which deck covering requiring a flush surface is to be laid, the top reinforcement shall be chipped or ground flush prior to compartment strength and tightness tests.

In making multiple layer butt or fillet welds, all slag adhering to each pass of the weld deposit shall be carefully removed before subsequent weld metal is deposited.

Peening and Calking.—Peening, the deep mechanical working of the weld metal, may be done to correct distortion or to minimize residual stresses, except that peening shall not be done generally on single bead or single layer welds, or on the first and last layers of multiple layer welds. Where, in special cases, circumstances make it impracticable to comply with the above requirement, the procedure that is to be used shall be approved by the Supervisor of Shipbuilding. Peening and calking of welds shall be done with a power hammer using a round-nosed tool. Peening shall, in general, be done at the completion of the deposition of each electrode, as soon as the slag has been properly cleaned off.

Finish of Welds.—Welds shall not be dressed, smoothed or finished for the purpose of improving their appearance, unless specifically called for in these or the detail specifications, or on the contract plans.

Where any weld metal, either temporary or permanent is removed from surfaces exposed to view and is not to be replaced, the areas so exposed shall be made as smooth as the unwelded surrounding structure. In locations not exposed to view, weld metal shall be removed when such weld metal constitutes a hazard to personnel and to equipment. In removing welded material, care shall be employed not to tear out or gouge the base metal. Such holes or undercutting as may result shall be filled by welding.

When grinding or chipping welds, care shall be taken to avoid undercutting or nicking the surface of the plate in the vicinity of the weld.

The outside surface of welds in the outer shell of the vessel shall be reasonably smooth. If the surface of the deposited weld metal is too rough, the Supervisor of Shipbuilding may require chipping, grinding or rewelding to obtain satisfactory smoothness. Care shall be taken that the thickness of the reinforcement of butt welds upon the completion of these operations shall be within $^1/_{32}$ to $^1/_8$ in.

Separate sections are also given in the Specifications for such items as Cleaning and Protection of Welds, Straightness of Structure, Deck Studs, Piping, Special Alloys, Gas Cutting, Silver Brazing, Tests and Inspection.

MERCHANT SHIPS

Probably the greatest single factor in bringing about the use of welding in merchant ship construction has been the application of the rules of the American Bureau of Shipping. The material which follows was taken largely from these rules, which, of course, should be consulted for complete information.

General.—The use of electric arc welding which complies with the requirements of the Bureau will be accepted for all parts of the ship, including those subjected to the principal structural stresses.

*Approval of Procedure.**—The approval of the procedure to be used in the welding of the various structures covered by these Rules shall be based

* For specific requirements consult the current Rules of the American Bureau of Shipping.

on its demonstrated suitability for the particular construction involved. When new methods, changes in base material or electrodes are proposed, test specimens are to be prepared under the new conditions from materials similar to those proposed for the construction.

*Qualification of Operators.**—An agreement recently concluded between the Navy, the Bureau of Marine Inspection and Navigation and the American Bureau of Shipping permits the acceptance of welders qualified by one of these bodies by each of the others. These requirements are identical with the AMERICAN WELDING SOCIETY qualification requirements (see Chapter 29).

*Workmanship and Supervision.**—The Bureau Surveyors must be satisfied with the operators' qualifications, the Builder's supervision and inspection, and that conditions for welding are such that good work is possible in accordance with generally accepted good practice.

*Electrodes.**—The requirements of the Bureau correspond very closely with those of the AMERICAN WELDING SOCIETY (see Chapter 27), but certification is required of the manufacturer.

The following are extracts from the American Bureau of Shipping Rules relating to Ship Welding:

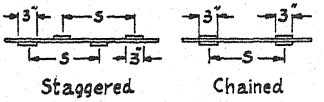
Table A—Spacing of Intermittent Welds

ITEMS		All fillets 3 Inches long				
		Plate thickness "t"				
		Not over .32 Inches	Above .32 to .42 incl. Inches	Above .42 to .52 incl. Inches	Above .52 to .62 incl. Inches	Above .62 to .72 incl. Inches
	Nominal size of fillet "w"	¼	5/16	3/8	7/16	½
† Beams	To decks when on alternate frames and in tanks	11	11	11½	12	12
	To decks when on every frame outside tanks	12	12	12	*12	*12
† Bulkhead stiffeners	Deep tank bulkhead. See Note A	10	10	10½	11	11
	Ordinary watertight bulkhead See Note A	12	12	12	*12	*12
	Non-watertight bulkhead See Note A	*12	*12	*12	*12	*12
Center girders	To inner bottom or rider plate in way of engines and to shell or bar keel	5	5	5½	5½	5½
See Note B	To inner bottom or rider plate clear of engines	6	6	6	7	7
† Frames and floors	To shell on flat of bottom forward and in aft peaks of vessels having high power and fine form	5	5	5½	5½	5½
	To shell for .15L forward to above load water line and in deep tanks and peaks	10	10	10½	11	11
See Note C	To shell elsewhere where spacing exceeds 30". See Note A	11	11	11½	12	12
	To shell elsewhere where spacing 30" or less. See Note A	12	12	12	*12	*12
Floors, single bottom	To center keelson plate in machinery space, wide spaced floors with longitudinal frames and within ½ length in vessels 230 ft. long and above			Double continuous		
	To center keelson plate elsewhere	7	7	7½	7½	8

*Nominal size of fillet "w" may be reduced 1/16 inch in association with spacing given.
†In vessels classed for River, Harbor or Canal Service exclusively the welding of beams, bulkhead stiffeners, frames and floors to the plating may consist of 2½" fillets spaced 12" centers in dry spaces and 3" fillets spaced 12" centers in tanks.

* For specific requirements see the current Rules of the American Bureau of Shipping.

Table A (concluded)—Spacing of Intermittent Welds

ITEMS		All fillets 3 inches long				
		Plate thickness "t"				
		Not over .32 Inches	Above .32 to .42 incl. Inches	Above .42 to .52 incl. Inches	Above .52 to .62 incl. Inches	Above .62 to .72 incl. Inches
	Nominal size of fillet "w"	¼	5/16	3/8	7/16	½
Floors, double bottom	Solid floors to center vertical keel plate in engine room, under boiler bearers, on wide spaced floors with longitudinal frames, and in vessels where length exceeds 500 feet	4½	5	5	5	5
	Solid floors to center vertical keel plate elsewhere, and open floor brackets to center vertical keel	9	9½	9½	10	10
	Solid floors and open floor brackets to margin plate	7	7	7½	7½	8
	To inner bottom in engine room. See Note C	5	5	5½	5½	5½
	To inner bottom at forward end. See Note C	11	11	11½	12	12
	To inner bottom elsewhere	12	12	12	*12	*12
Foundations	Main engine girders to top plates, shell, or inner bottom			Double continuous		
	Boiler and auxiliary foundation girders to top plate	4½	5	5	5	5
	Boiler and auxiliary foundation plates to shell, inner bottom, and all brackets, etc.	5	5	5½	5½	5½
Solid webs under 27" deep	To shell and to bulkheads in tanks	9	9½	9½	10	10
	To bulkheads elsewhere	12	12	12	*12	*12
Solid webs 27" deep and over, slotted webs, stringers or girders under 27" deep	To shell and to bulkheads or decks in tanks	6	6	6	7	7
	To bulkheads or decks elsewhere	9	9½	9½	10	10
Slotted webs, stringers or girders 27" deep and over	To shell and to bulkheads or decks in tanks	4	4	4½	4½	4½
	To bulkheads or decks elsewhere	7	7	7½	7½	8
All Face Plates	To webs where area is 10 square inches or less	12	12	12	*12	*12
	To webs where area exceeds 10 square inches	7	7	7	8	8
Intercostals	To shell on flat of bottom forward, and to inner bottom in way of engines	5	5	5½	5½	5½
	To shell and inner bottom elsewhere	10	10	10½	11	11
	To floors	10	10	10½	11	11

* Nominal size of fillet "w" may be reduced 1/16 inch in association with spacing given.

NOTE A—Unbracketed shell and bulkhead stiffeners are to have double continuous welds for one-tenth of their length at each end.

NOTE B—Where center girders are water or oil-tight a continuous weld is to be used on one side of the top and bottom connections with intermittent welds on opposite side spaced 12 inches.

NOTE C—Tank end floors are to be welded to shell, center girder and inner bottom as required for deep tank bulkheads.

NOTE D—Where beams, stiffeners, frames, etc., pass through slotted girders, shelves or stringers, there is to be a pair of matched intermittent welds on each side of each such intersection and the beams, stiffeners, and frames are to be efficiently attached to the girders, shelves, and stringers.

Details of Joints.—(*a*) The following details of joints are intended as standards to be followed in association with ordinary manual arc welding, but the Bureau is prepared to consider other forms of joints which may be proposed by individual builders to suit special conditions or special welding processes. In such cases it may be required that specimen joints be submitted for examination and testing. Such joints are to be prepared by using the same equipment and materials and under approximately the same conditions as will prevail in the actual construction.

(*b*) In general, unstrapped butt joints of plating not exceeding 0.2 in. in thickness may be made without bevelling the plate edges; otherwise the edges on one side or both sides of the plate are to be bevelled to a total angle of 60°, preferably leaving a shoulder of $^1/_{16}$ to $^1/_8$ in., depending on the plate thicknesses. In all cases the gaps between plates in such joints should be kept to a minimum and the welding applied to the reverse side only after it has been chipped and cleaned thoroughly. If details other than the foregoing are proposed to be used, such details are to be submitted specially for approval and should be accompanied by reports of qualification tests (as for an operator) made in the presence of the Surveyors.

(*c*) In general, strapped butt joints are to be made by preparing the plate edges in a manner similar to that described for an unstrapped joint having a bevel on one side of the plates. The strap, fillet welded to the opposite side of the plates, should have a width of at least twice the thickness of the thinner plate and a thickness not less than one-half that of the thinner plate. The gap between the bevelled plate edges may be from $^1/_8$ to $^1/_4$ in., depending on plate thicknesses. In no cases shall the middle of such a strapped butt joint be welded last. If details other than the foregoing are proposed to be used, such details are to be submitted specially for approval and should be accompanied by reports of qualification tests (as for an operator) made in the presence of the Surveyors.

(*d*) Lapped joints are generally to have overlaps of not less width than twice the thinner plate thickness plus one inch. Where one plate edge is joggled the width of the actual overlap may be reduced to a minimum of the thinner plate thickness plus one inch, provided that the joggle is to be fitted closely to the opposite plate edge. Both edges of an overlapped joint should have fillet welds which may be continuous or intermittent and of the sizes as required below.

(*e*) Tee joints are to be formed by either continuous or intermittent fillet welds on each side, as required below and in general, the required size and spacing of the fillets shall be determined by the thickness of the stem of the tee or the plate to which it is joined, whichever is lesser. If the stem of a tee joint does not bear directly upon the plate to which it is joined a properly fitted liner may be used, provided that such liner be wide enough to permit both to be welded with proper sized fillets.

Forms of Welds Required.—(*a*) All joints are to have "light," or "full" fillet welds, which may be continuous or intermittent, in accordance with the following general requirements.

(*b*) By "light fillet weld" is meant one in which the sides of the triangle equal at least one-half the thickness of the plates joined, while "full fillet weld" means similarly a fillet the full thickness of the plate edge.

(*c*) End connections of shell and deck plating may be of the unstrapped butt-joint type. When of the unbevelled strapped-butt or overlap type of joint, the edges should be full fillet welded except at the extreme ends of the vessel, where they may have fillets as required for seams at corresponding thicknesses and tightness. When of the bevelled strapped-butt type, the edges of the straps are to have light fillet welds.

(*d*) End connections of girders and webs should be as required for shell and deck plating amidships. Those for bulkheads may be as required for the corresponding seams.

(*e*) The fillet welds of overlapped seams of plating and of tee-joint boundary connection of bulkheads, decks, flats or inner bottom should be continuous on both sides where the plating is 0.50 in. thick or greater. In general, the fillets should be at least equivalent to a combination of one of $^1/_{16}$ in. less than the thinner plate thickness on one side and one of one-half the thinner plate thickness on the other side. The fillet on each side of all overlapped end connections of longitudinal strength members should be continuous and of a size at least equal to $^1/_{16}$ in. less than the thickness of the edge of the plate to which it is applied.

(*f*) The fillet welds of overlapped seams of plating and of tee-joint boundary connections of bulkheads, decks, flats or inner bottom are to be continuous on one side (outside of shell plating and top of deck plating) and may be intermittent on the other side where the plating is less than 0.50 in. in thickness. In general, the fillets should be at least equivalent to a combination of one continuous fillet $^1/_{16}$ in. less than the thinner plate thickness on one side and on the other side an intermittent weld having fillet sizes and spacing as required for the thinner plate by Table A for deep tank stiffeners, except in way of oil tanks where equivalent light continuous welds are to be substituted.

(*g*) Frames, beams, bulkhead stiffeners, floors and intercostals, etc., are to have at least the disposition and sizes of intermittent welds of the fillet form as required by Table A or an equivalent disposition for strength, but in no case shall the spacings exceed the maximum of 12 in. as given in the table.

(*h*) Where it is desired to substitute continuous welding for intermittent welding as given in Table A, a reduction of $^1/_{16}$ in. from the required size of fillet may in general be allowed, but the actual sizes of the fillets are subject to approval in each individual case.

The foregoing are considered minimum requirements for electric welding in hull construction, but alternate methods of arrangements and details will be considered for approval.

SHIP WELDING TODAY

The real test of any ship structure is its proved efficiency under service conditions throughout the useful life of the ship, and so far our all-welded ships have been reliable. However, this fact should not allow us to be lulled into any false sense of security for the future, as the application of welding to large ocean-going ships constitutes a problem which must continue to be approached conservatively along sound scientific lines. For example, considerable research is under way on the question of residual stresses, a subject on which there is a wide diversity of opinion. Pending a complete solution of this problem it will be well to follow such welding technique and procedure as will tend to keep those so-called locked-up stresses to a minimum. Distortion and shrinkage allowances are practical problems which can best be solved by the interchange of opinion and data between our shipyard welding engineers, based on their individual experiences.

The all-welded ship is comparatively new and offers a wide field for the

exercise of ingenuity in the development of new methods and machines to speed up production. It is safe to predict that welding machines and electrodes will continue to improve, and that there will be further developments in automatic welding equipment which will facilitate the production of high quality welds at lower costs. It is up to the shipbuilder to continue to improve methods of design, fabrication and assembly if the fullest advantage is to be taken of the new process. Fusion arc welding has reached that stage of development which establishes it as a method of joining structural parts which is unquestionably superior to riveting.

CHAPTER 40B

AIRCRAFT TUBING*

Welding Processes, Materials, Filler Metal, Design of Joints, Heat Treatment, Manufacture, Inspection.

WELDING of all types has taken great strides during recent years in the aircraft industry. It is today an integral part of aircraft manufacture. In order to achieve a maximum strength with lowest weight and greatest economy possible a multiplicity of joints is required, and it is here that welding plays its important role. No rivet or bolt holes are needed and, as a result, simplicity, rigidity and relatively high strengths are obtained in the structure; and, in addition, there is the possibility of considerable saving of time and material. The process is applicable to all craft from the smallest private sport airplane to the largest commercial transport and military types. The characteristics and reliability of welded joints have been tested thoroughly in the laboratory and in service under a variety of operating conditions. In all respects these joints when properly executed by trained personnel have been proved entirely satisfactory. Recent developments of both ferrous and non-ferrous materials which may be suitably and easily welded have greatly aided the advance of welding to its present position.

Welding Processes

Electric Arc Welding is becoming an increasingly important process in the manufacture of aircraft structures. Constant research is producing welding machines of increasing reliability and greater flexibility. Introduction of accessory appliances to prevent crater formation, heretofore a serious obstacle, is one of the chief improvements. Material as thin as 0.035 in. is welded regularly.

Electric Flash Welding.—Whenever production justifies heavy capital investment in equipment, flash welding of mild and alloy steel tubes can be and is frequently used. Though at present in the aircraft industry it is closely confined to comparatively small sections, rapid developments are now under way in adapting its use to very much heavier sections such as are encountered in engine mounts and landing gear.

* Prepared by a committee consisting of C. J. Gallant, North American Aviation, Inc., *Chairman;* J. P. Dods, Summerill Tubing Co.; J. B. Johnson, U. S. Army Air Corps; Bernard Gross, Ryan Aeronautical Co.; R. A. Webster, Douglas Aircraft Co.

Oxyacetylene Welding is widely used particularly because of its flexibility, the lack of skilled arc welding operators and the impracticability of using other methods in fabricating minor fittings such as tube clamps, lugs, etc.

Oxyhydrogen Welding is another variation of the gas-welding process. It is being used for the welding of low stressed parts of aluminum and non-heat-treatable aluminum alloys in the manufacture of fuel, oil, water tanks, etc.

Atomic Hydrogen Welding, although employed in the industry, is not flexible enough to find wide-spread application. It is used for assemblies

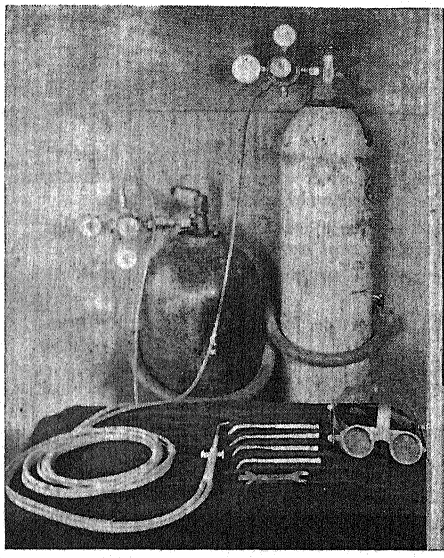


Fig. 1—Oxyacetylene Equipment

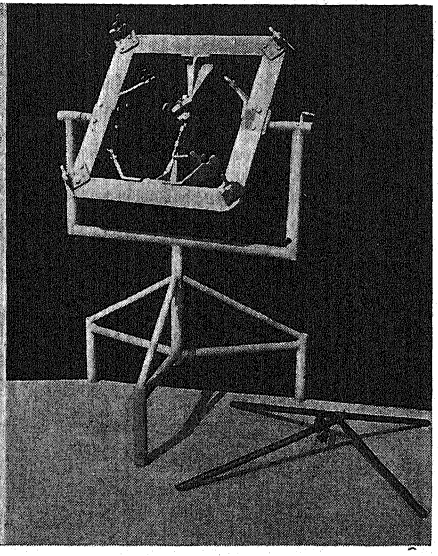


Fig. 3—Welding Jig for Small Assemblies

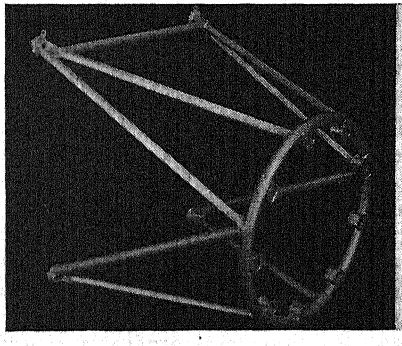


Fig. 2—Arc-Welded Motor Mount

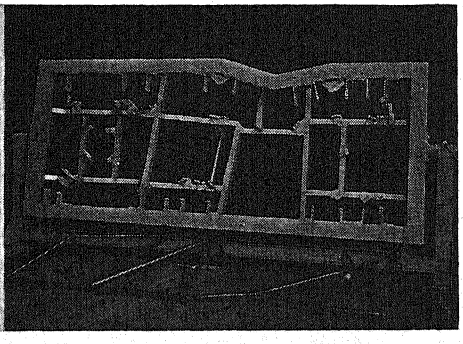


Fig. 4—Fuselage Subassembly Jig-Note Rotation Possible

fabricated from chrome-vanadium and chrome-nickel-molybdenum sheets in horizontal jigs.

Manufacture

It is difficult to design an assemblage of tube, plate and forgings which after welding, heat treating and quenching will have strength uniformity commensurate with acceptability. Consequently, the engineer confronted with joints of this nature must employ skill and ingenuity both in the use of materials which do not require heat treatment and in the design of such joints.

In welding X4130 steel the engineer should avoid, where possible, the following practices:

1. A joint between very thin and heavy metal, as the heat required to bring the heavier member up to the welding temperature may burn or melt away the thin metal.
2. The convergence of more than six members to form a welded cluster. The repeated applications of heat on the small area where all members meet, weaken the base metal adjacent to the re-melted weld metal.
3. The use of tin-lead solder in proximity to a joint so that repair of the joint might cause contamination of the weld metal by the solder.
4. Welding of a brazed joint. The reverse practice of brazing a welded joint is permissible.
5. A joint which requires welding at the inside junction of two members forming an acute angle.
6. Joints in parts which are heat-treated before welding, especially for a required tensile strength in excess of 125,000 psi.

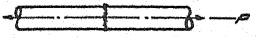
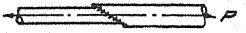
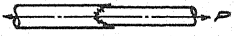
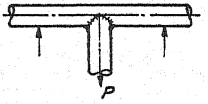
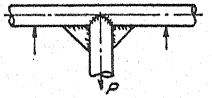
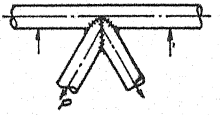
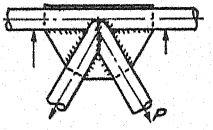
Joints made with plain butt welds (unless fabricated by flash welding), plain telescope or lap welds, tapered welds with angles greater than 30° to the center line, or fish mouth welds greater than 60° are designed on the basis of a maximum tensile strength of 80,000 psi. in the case of X4130 and 45,000 psi. in the case of medium carbon steel (Table 1).

Joints made with tapered welds at angles of 30° or less to the center line, or fish mouth welds at an included angle of 60° or less are designed on the basis of a tensile strength of 90,000 psi. for X4130 and 50,000 psi. for medium carbon steel.

Breakdown tests are the basis for approved design. The strength of the joint will depend on the strengths of the base metals, the weld (filler) metal and the changed characteristics in the heat-affected zone.

In designing jigs consideration should be given to accessibility, ease of loading and unloading, and rigidity. Jigs have been designed for all sizes of work from parts small enough to be bench welded to entire fuselage structures. Even in the case of large size jigs, the frame may be mounted on trunnions in order that the entire assembly may be rotated (Fig. 4). For very large assemblies, such as entire fuselages, this rotation may not be possible. In this case both vertical and overhead welding will be required. Because of this aircraft welding operators must be qualified for all positions of welding. The design of jigs must allow for expansions due to heat generated during the welding and at the same time prevent warping of the welded parts. Electric arc welding has a small area of heating which tends to lessen these expansion allowances.

Table 1—Allowable Stresses in Different Types of Joints

	Type of Weld	Tension and Compression Allowable Unit Stress Base Metal, Psi	
		1025	X4130
	Butt	45,000	80,000
	Scarf	50,000	90,000
	Fish mouth	50,000	90,000
	Tee	35,000	55,000
	Tee with gussets	45,000	75,000
	Lattice	35,000	60,000
	Lattice with gussets	40,000	75,000

Electric arc welding has greatly benefited from the development and introduction of the crater eliminator.* It must be borne in mind that a good appearing surface often hides serious defects which will only become apparent through destruction of the weld or by X-ray examination (Figs. 5 and 6).

Inspection

In production, weld inspection must be such that the weld is not damaged. The periodic welding of test coupons or periodic sampling of production lots afford the means for destructive inspection but due to the time involved for a complete analysis of this kind assembly line methods are usually employed. (See Fig. 13.)

Visual inspection is the most used method. An experienced inspector can usually determine the nature of a weld by this means. However, as

* A device switched on by the pressing of a button by the operator which automatically reduces the current at the end of the weld.

has been stated above, a clean, good appearing surface is not necessarily a criterion for a strong weld. A well-formed bead usually implies expert welding and good workmanship throughout.

Welded tube assemblies are normally air-pressure tested and checked for leaks with a brushed-on soap solution prior to filling with hot linseed or petroleum base oils. Defects are indicated by bubbles at the cracks.

Magnetic inspections are also being used. The welded joint is mag-



Fig. 5—Comparison of Arc Welds Made with and without the Use of the Crater Eliminator—(X4130 Steel Photomacrographs)

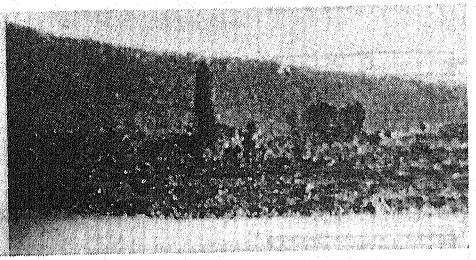


Fig. 6—Photomacrograph Showing How Weld Appearance May Fail to Disclose Flaws—Weld Ending Made by Lengthening Arc

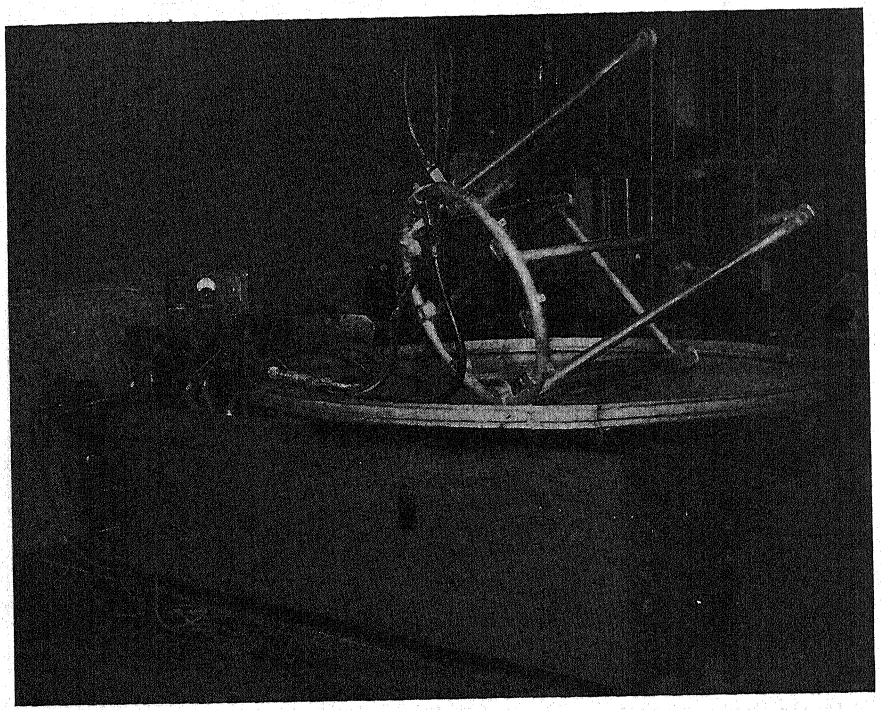


Fig. 7—Magnaflux Machine Motor Mount Test Set-Up

Table 2—Ferrous Materials

FORM	S.A.E. NUMBER	SPECIFICATION	CHEMICAL COMPOSITION									MECHANICAL PROPERTIES (MIN.)		
			C	Mn	P (4)	S (4)	Cr	NI	SI	Mo	Other	Yield	U. T.	% Elon
Chrome-moly sheet (1)	X4130	AN-QQ-S-685	0.25-0.33	0.40-0.60	0.040	0.050	0.80-1.10			0.15-0.25		70,000	90,000	10-18
Chrome-moly bar (1)	X4130	AN-QQ-S-684										100,000	125,000	18
Chrome-moly tube (1)	X4130	AN-WW-T-850										75,000	95,000	12
Chrome-moly bar (2)	4140	AN-QQ-S-752	0.35-0.42	0.60-0.90	0.040	0.050	0.80-1.10			0.15-0.25		100,000	125,000	18
Chrome nickel sheet (3)	30905	AN-QQ-S-757	0.08 (4)	0.2-2.5	0.03	0.03	17.0-20.0	7.0-12.0	0.2-1.5		Cb 0.80 Ti 0.40	---	100,000 (4)	40
Chrome nickel tube (3)	30905	AN-WW-T-858										---	100,000 (4)	35
Chrome nickel sheet	30915	AN-QQ-S-772	0.12 (4)	0.2-2.5	0.03	0.03	17.0-20.0	7.0-12.0	0.2-1.5		Cb, Ti optional	75,000	125,000	20-25
Chrome nickel bar	30915	AN-QQ-S-771										75,000	125,000	15
Low carbon bar	1025	AN-QQ-S-646	0.20-0.30	0.30-0.60	0.045	0.055						36,000	55,000	22
Low carbon tube	1025	AN-WW-T-846										36,000	55,000	22

(1) Normalized condition
(2) Quench hardened and tempered condition
(3) Annealed condition
(4) Maximum value

netized and flooded with a kerosene suspension of ferromagnetic particles. The presence of a crack will cause a number of particles to align themselves along the surface at the site of the crack (Fig. 7).

X-ray inspection of welds is difficult and time consuming because of the inaccessibility of many joints and the necessity of taking pictures from several angles in order that a true determination may be made.

Materials

Chrome-Molybdenum Steels (Tables 2, 3 and 4)

The development of S.A.E. X4130 of so-called "aircraft quality" has lead to the employment of this steel in the majority of welded steel assemblies. The composition of the alloy is such that it is easily weldable and the air-hardening properties permit a higher allowable stress than is possible with other steels. The joint in the "as-welded" state develops

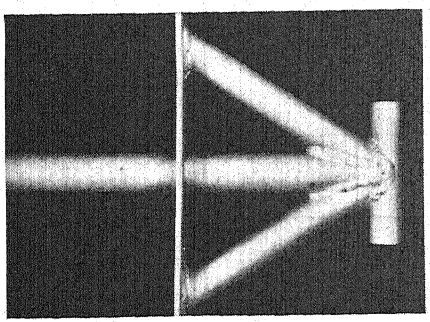


Fig. 8—Tube Into Cluster with No Gusset—Arc-Welded

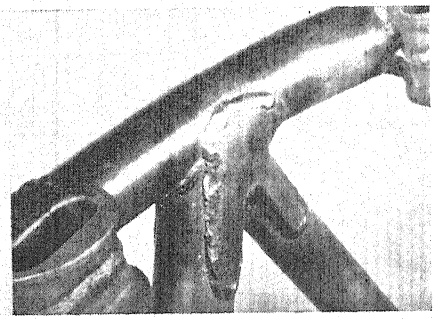
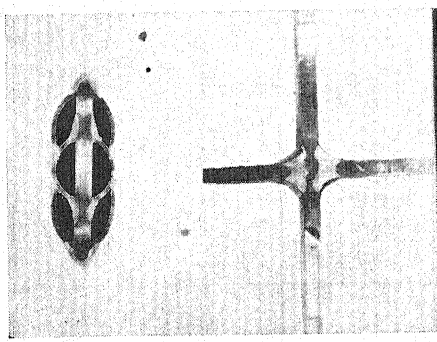
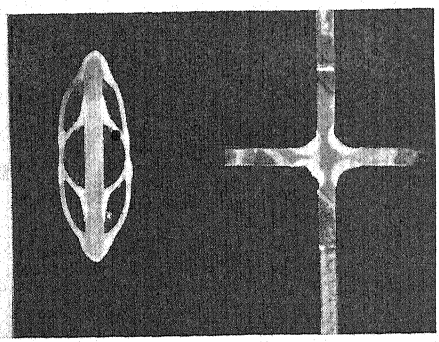


Fig. 9—Arc-Welded Gusset Plate on Motor Mount





Figs. 10 and 11—Comparison of Arc- and Gas-Welded Joints

No. 10—Arc-Welded No. 11—Gas-Welded

at least 80% of the original properties of the parent metal. Heat treatment of the joint subsequent to welding is not essential. This feature is

Table 3—Characteristics of Welded X4130 Tubing

(1 In. O.D. x 1/16 In. Wall Thickness)

Type of Joint	Filler Metal	Heat Treat, After Welding	Tensile Strength of Joint (Psi)	Fatigue Strength of Base Metal (Psi)	Fatigue Strength of Joint (Psi)
Butt (1)	L. Carbon	None	95,000	41,000	16,000
Butt (2)	None	None	100,000	41,000	24,000
Butt (1)	L. Carbon	950°F.—1/2 hr.	95,000	41,000	18,000
Butt (2)	None	950°F.—1/2 hr.	103,000	41,000	32,000
Butt (1)	L. Carbon	1650°F.—1/2 hr.	90,000	....	16,000

(1) Oxyacetylene.
(2) Flash.

Table 4—Characteristics of X4130 Tubing

(Various Diameters—Not Heat-Treated After Welding)

Analysis					Tensile Strength, Psi.	Yield Point, Psi.	Elongation 2 In., %
C, %	Mn, %	Cr, %	Mo, %	Specimen			
0.28/0.35	0.30/0.60	0.90/1.0	0.15/0.25	Unwelded	98,000	75,000	12.0
0.28/0.35	0.30/0.60	0.90/1.0	0.15/0.25	Welded	96,000	72,000	7.0
0.25/0.35	0.40/0.60	0.80/1.10	0.15/0.25	Unwelded	95,000	60,000	..
0.25/0.35	0.40/0.60	0.80/1.10	0.15/0.25	Welded	80,000	50,000	..

"Molybdenum in steel"—Climax Molybdenum Company.

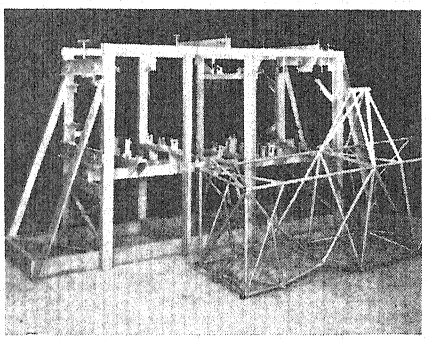


Fig. 12—Fuselage Assembly Jig

especially favorable in the case of fuselage structures where heat treating would be very costly. However, many manufacturers favor normalizing of the welds.

The manufacture of seamless tubing for aircraft requires practically the same processes and equipment as are required in the fabrication of other types of seamless steel tubing. However, greater care is taken both in the fabrication of the product and in the control of the purity of the alloy. The tubing must be uniform and free from defects of composition and structure.

In addition to X4130, S.A.E. 4140 is also used in aircraft manufacture, especially for parts containing thick sections and for forgings. If 4140 is used, fusion welding should be followed by heat treatment.

X4130 is fusion welded either by the electric arc or the oxyacetylene process. Two types of filler material are used, dependent upon the thickness of the metal to be welded. For tube and thin plate, low carbon steel electrodes are used. For material $^{3}/_{16}$ and heavier, heat-treatable alloy steel electrodes of the following approximate composition are also used; although the alloying elements may be incorporated in the coating rather than in the steel.

Carbon	0.11%
Vanadium	0.08%
Manganese	0.41%
Molybdenum	1.01%
Sulphur	0.045 (max.)
Phosphorus	0.045 (max.)

Little or no processing of the material is required before welding. Some assemblies are preheated to advantage, but the practice is by no means universal except on steels containing over approximately 0.35 per cent

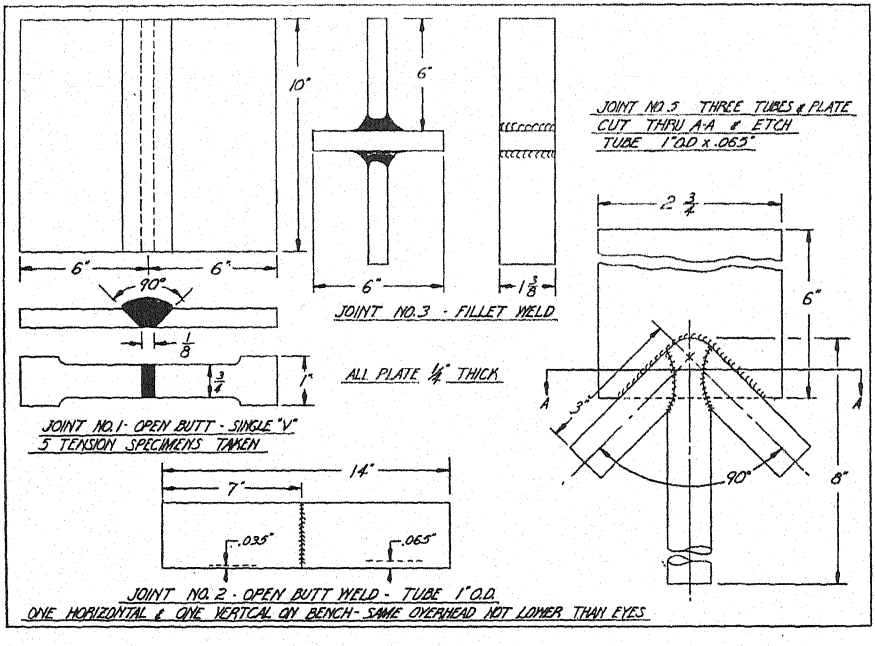


Fig. 13—Qualification Test for Aircraft Welders

carbon. The edges of the joints do not require special cleansing other than ordinary precautions to prevent excessively dirty or heavy scaled surfaces. Cleaning of the weld may be accomplished with a wire brush although sand blasting is more generally used due to the practicability and economy afforded.

CHAPTER 40C

RAILROADS*

Machine Gas Cutting and Welded Fabrication of Locomotive Cylinders Using Rolled Steel Plate, Welding in Tank Car Construction, Welded Passenger Cars, Welded Box Cars, Resistance Welding of Freight Cars, Repairing Welded Stainless Steel Passenger Cars, General Welding Practice on Locomotive Boilers and Tenders, Railway Track Welding.

INTRODUCTION

IN THE early days, welding received its major impetus in the railroad field, where its applications are now so numerous that a large book would be required to fully describe them. Therefore, the Committee has selected a reasonable number of the major applications. These selections necessarily represent the painstaking developments of the individual manufacturing companies, railroads and organizations with which the authors are connected. It is not intended to imply that these Sections represent complete coverage of the whole field.

MACHINE GAS CUTTING AND WELDED FABRICATION OF LOCOMOTIVE CYLINDERS USING ROLLED STEEL PLATE

One of the recent and interesting developments and applications of the machine gas cutting and arc-welding processes is the production with fabricated steel plate sections of all welded locomotive cylinders, which though about 15% lighter, are nevertheless stronger than the cylinders formerly used. (Figs. 1 to 4.)

The fabrication of these cylinders is another step forward in the production of modern locomotives.

Dual type locomotive cylinders of all-welded construction are now being used by the Pennsylvania Railroad. These cylinders are built at their

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* Prepared by a committee consisting of H. L. Miller, Republic Steel Corp., *Chairman;* J. G. Adair, Bureau of Locomotive Inspection; Rupen Eksergian, E. G. Budd Mfg. Co; H. E. Gannett, C., B. & Q. R.R Co.; Leland E. Grant, Chicago, Milwaukee, St. Paul & Pacific R.R.; H. A. Hocking, Air Reduction Sales Co.; H. M. Priest, Railroad Research Bureau, United States Steel Corporation Subsidiaries; J. W. Sheffer, American Car & Foundry Co.; A. M. Unger, Pullman-Standard Car Mfg. Co.

Altoona Works Shops, Altoona, Pa. They weigh and cost less than dual type cylinders of other construction.

The first all-welded cylinder on the Pennsylvania R.R. was placed in service Feb. 1, 1939. An additional three were also placed in service in 1939. Twenty-four were placed in service in 1940 and so far nine have been placed in service in 1941, making a total of thirty-seven now in active service on this railroad. Their service records have been very satisfactory.

Each cylinder required about 1050 lineal feet of cutting. The steel plates were of flange quality with a carbon range of 0.20–0.30% and in thicknesses of $^1/_2$ in., $^3/_4$ in., 1 in., $1^1/_4$ in. and $1^1/_2$ in.

The finished machined weight of the welded cylinder was approximately

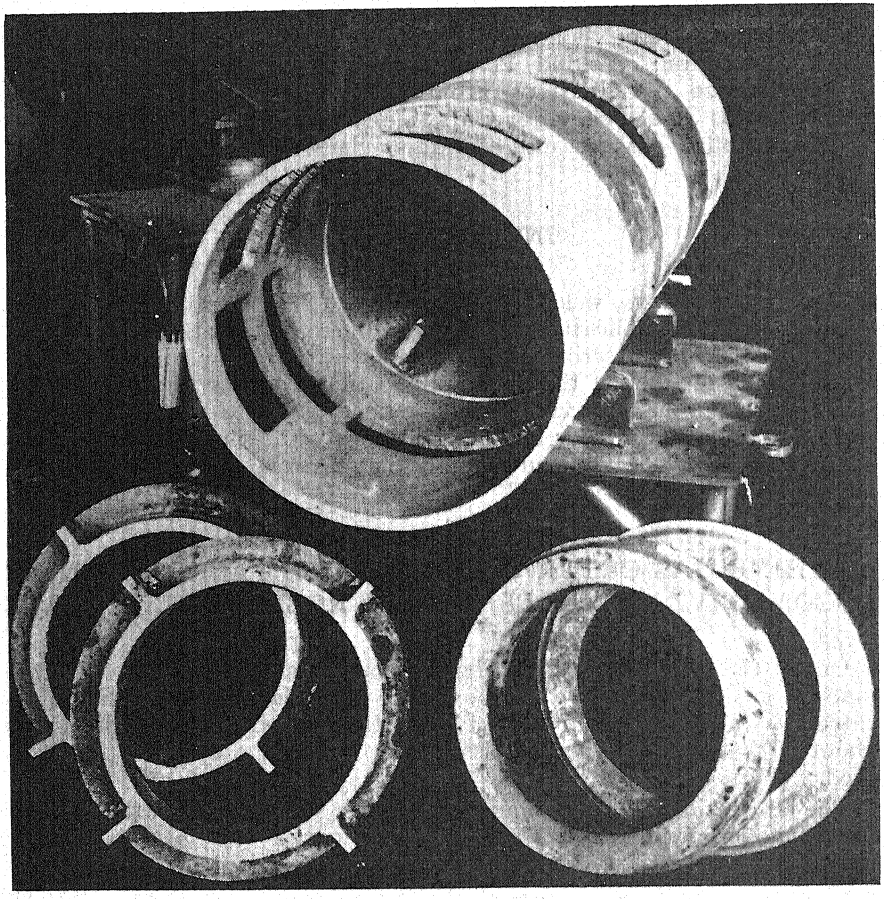


Fig. 1—Valve Chamber Barrel on Table Equipped with 4 Rollers to Turn Barrel While Welding the Center Bushing Supports to Inside of Barrel. Round Bushing Supports Shown on the Floor Are Assembled and Welded in the Barrel

13,600 lb. which, as before stated, was about 15% lighter than other constructions previously used.

About 1350 lb. of shielded arc electrodes were used in making each cylinder.

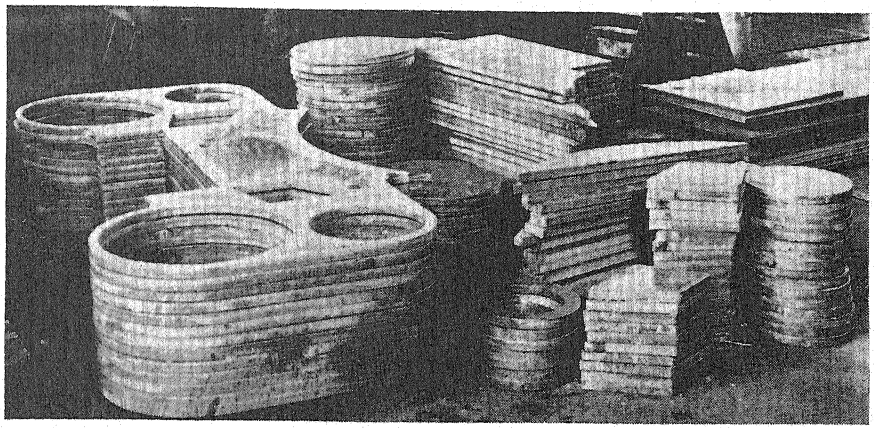


Fig. 2—Quantity of Cut Parts Ready for Assembly and Fabrication by Welding

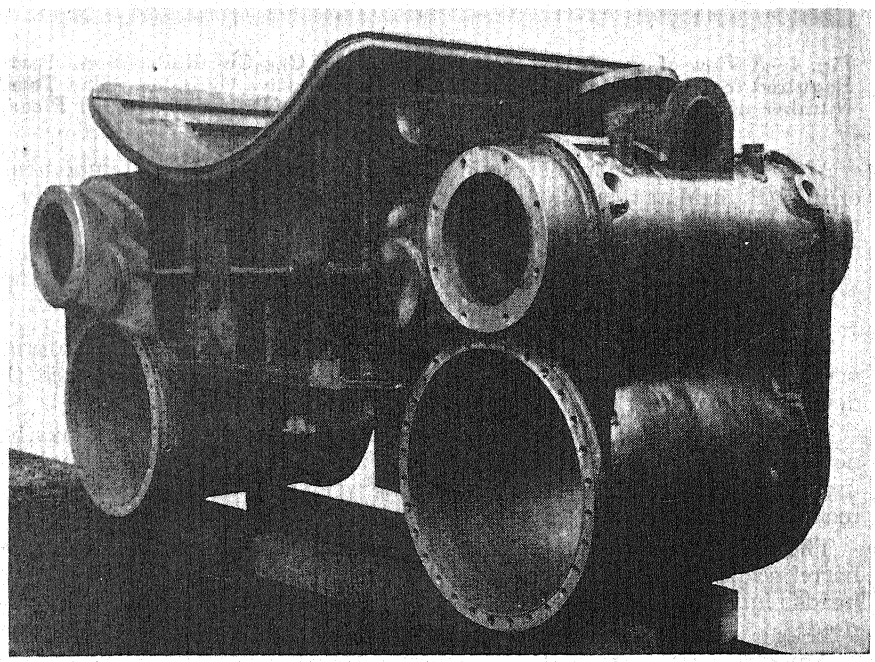


Fig. 3—Side and Front View of a Completed Cylinder

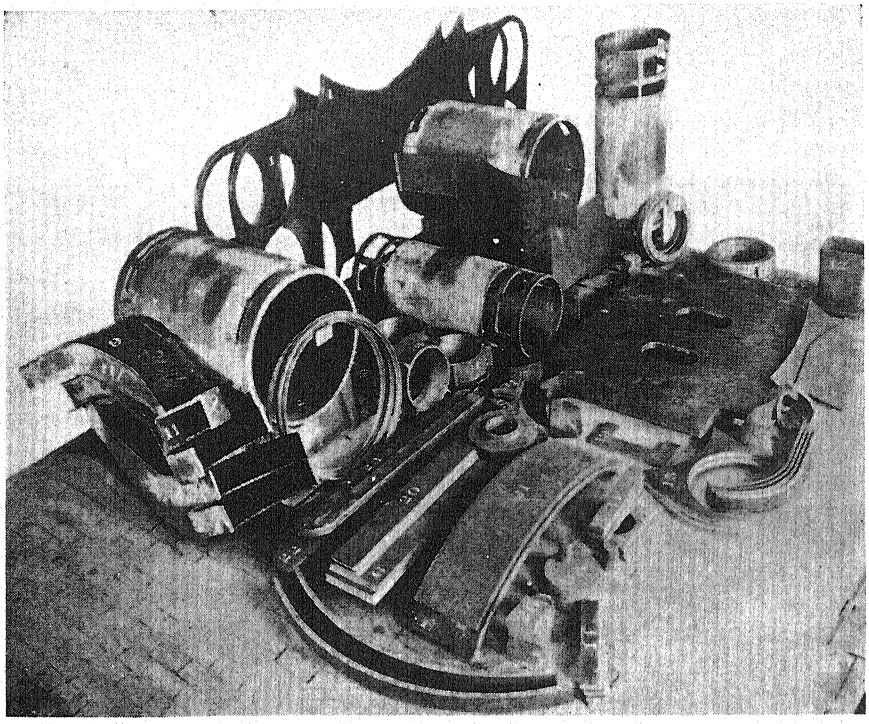


Fig. 4—A View of the Entire Group of Machine Gas-Cut Rolled Steel Parts Required for the Welded Fabrication of a Locomotive Cylinder. The Total Number of Pieces Used Are 177, of Which 53 Are Different Shaped Pieces

After welding, the complete cylinder was stress-relieved at a temperature of 1050°F., held at this temperature for five hours and cooled uniformly in the furnace.

WELDING IN TANK CAR CONSTRUCTION

The demand for lightweight Rolling Stock has brought new material, new designs, new welding methods, which in turn have necessitated the development of new equipment and new technique.

The application of welding to the various classes of tank car tanks has not permitted the car designer to reduce materially the weight through the use of lighter gage plates even though the welded seam has a substantially increased strength value (Fig. 5).

The use of the butt seam in the welding of both the longitudinal seam and barrel seam tank has eliminated the overlapping of the seams and rivet heads required with the riveted tank. Therefore, narrower sheets may be used.

Any structure or element of a structure that is a part of a railway car is subjected to vibrations and a greater variety of shocks than is found in any

permanent structure, be it building, bridge or the enormous stills used in the petroleum cracking process.

The uniform thickness of shell of the welded type of construction is not possible in the riveted type. Where the sheets of a riveted seam overlap, a fairly rigid band is formed.

Any tank built out of thin plates such as is permissible in the I.C.C.-103 group specifications, breathes—that is, when it is not loaded or is partially loaded but not under pressure, the tank is not cylindrical but elliptical in cross-section.

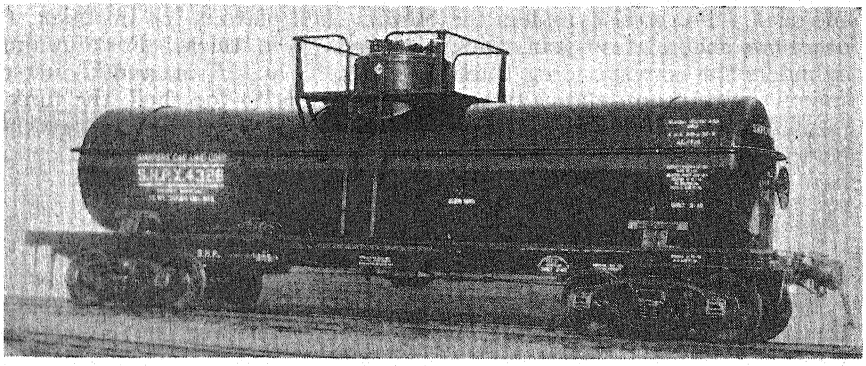


Fig. 5—Single-Compartment Insulated Tank, Automatic Fusion Welded

If the shell is of uniform thickness this breathing will be uniform to a large degree over the entire cross-section of the tank. Where the tank is not uniform, that is, where the tank has riveted seams or bands, there is an unequal distortion of the metal due to this breathing which has a tendency to open up the joints and start leaks. On the welded tank, assuming that a good job of welding is done, there is little possibility of leaks developing.

The welded tank has a relatively smooth interior. There are no rivet heads projecting. This smoothness is especially desirable for tanks which are to be lined either with lead or more especially with rubber, or even with some of the spray materials.

The use of the X-ray process to explore all-welded seams and the stress relieving of the entire tank put quite a cost burden on the welded tank.

The fabrication of tank car tanks by the fusion welding method has had a long uphill struggle extending over several years. Special authorization had to be secured from the I.C.C. for each order for specified experimental service.

Recently permanent specifications covering the construction of fusion welded tanks were recommended by the A.A.R. Tank Car Committee to the I.C.C.

The development of production methods and the installation of production welding equipment that will give a normal production and a quality of

output through fabrication by welding, equal to or better than riveting, have now become accomplished facts.

Several fusion welding processes have been approved by the A.A.R. Tank Car Committee. The one selected for any specific case will depend upon the fabricator's experience, facilities and methods.

At present the automatic submerged melt process is used more than any other in the construction of steel tanks. It is fully described in Chapter 7.

The shielded automatic carbon arc process is used more than any other in the construction of aluminum tanks. It is fully described in Chapter 4D.

Tank car tanks have an outside diameter of 78 in. and an over-all length of 32 ft. Each cylinder is made of three plates running the full length of the shell. For steel cylinders the bottom shell plate is $^{7}/_{16}$ in. thick, the other two shell plates $^{5}/_{16}$ in. thick, the heads $^{1}/_{2}$ in. thick. For aluminum cylinders the corresponding thicknesses are $^{5}/_{8}$ in., $^{1}/_{2}$ in. and $^{5}/_{8}$ in., respectively. In automatically welding the heads to the shell, the tank is rotated beneath the arc with the inside of the seam backed up with copper bars or granulated material for submerged melt welding, and with copper bars for carbon arc welding.

WELDED PASSENGER CARS

Two general types of welded passenger cars are being built at the present time. These differ only in the type of side construction, one having spot-welded girder type sides, the other arc-welded truss frame sides sheathed with stainless steel.

The girder type of passenger car is built with flat sides. The smooth sides with no projections give a very pleasing appearance and are easy to clean.

Many problems had to be solved to produce the smooth side. In the old days of riveted cars, buckles in the side sheets were not particularly objectionable because the rows of rivet heads drew the attention of the eye. These evenly spaced rivets in straight rows camouflaged the dips and bulges in the car side sheets. When spot welds replaced the rivets in the car side there were no projecting rivet heads to hide the buckles. It therefore became necessary to make a flatter side with spot welding than had been made with riveting.

The first experimental panels that were spot welded showed that considerable trouble with buckling would be experienced. Spot welding of a car side consists of vertical rows of welds on the side posts and horizontal rows of welds on longitudinal framing members at the top and bottom of the side and at the top and bottom of the windows. This means that the car side is divided into panels having spot welds completely around their perimeter. The panels are formed above and below the windows and in between windows.

Each spot weld shrinks a certain amount. As a result of this shrinkage, a panel that is surrounded by a row of spot welds has its outer perimeter shortened. The natural result of this is to throw a bulge in the panel.

In a study that was made of buckles, it was found that, besides the buckles formed by the shrinkage of the spot welds, there were others

caused by shrinkage of arc welds on the framing. To prevent this from having any effect on the outside sheet, the frame is built separately and all the arc welding is completed before the frame is attached to the sheet.

To prevent the shrinkage of the spot welds that join the side sheet to the framing from causing buckles, the side sheet is stiffened by the addition of a very light-gage, corrugated stiffener spot welded to the outside sheet. This stiffener has strength enough to resist the stresses set up in the sheets by the shrinkage of the spot welds.

The side sheet of a car is divided into an average of 16 sections. These sections are joined by a horizontal butt weld into 8 vertical sections. The vertical sections are joined together by 7 vertical butt welds to form the complete side.

The horizontal and vertical butt welds are made with the Unionmelt machine shown in Fig. 6.

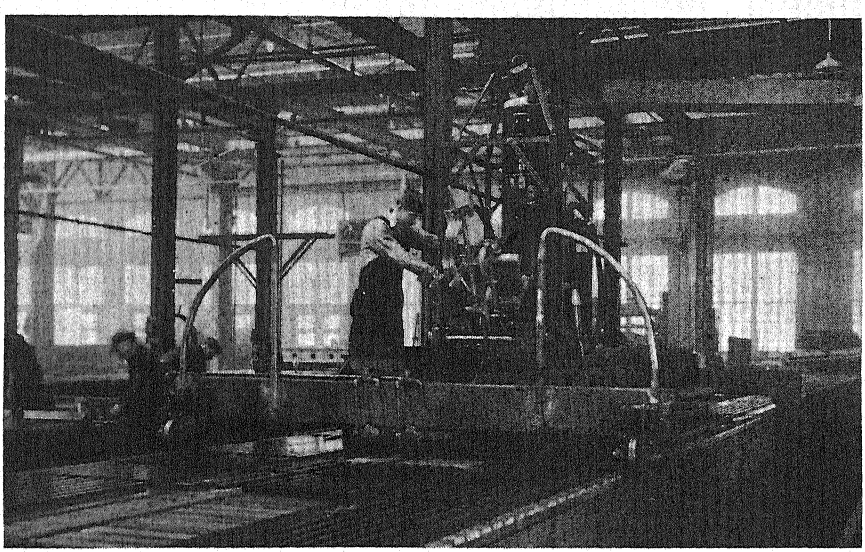


Fig. 6—Joining Side Sheets with Unionmelt Welding Machine

After grinding the weld bead flush on the outside surface, the sheet is clamped against a spot-welding jig. The side that is to be the outside of the car is placed against the jig.

The spot-welding jig consists of a supporting framework holding in a vertical position a copper plate 8 ft. 10 in. high and 85 ft. long. As the welds are made in series, the copper plate serves as a current-conducting backup to carry the current from one electrode to the other after it has passed through the side being welded.

A copper plate is used instead of individual backup bars so that no jig change will be required from one plan of car to another. No matter where the framing members are located, they are always backed up by the copper plate (Fig. 7).

The side frame is fitted and arc welded in a separate jig into one complete

unit. As mentioned before, all the arc welding is completed in this position so that the only welding that remains to be done is spot welding to the side sheet. After the arc welding is completed, the welds on the surface that goes against the side sheet are ground flush. The frame is checked for straightness, straightened and then clamped against the side sheet on the spot-welding jig.

The spot welding of the frame to the side sheet is done with the outside of the car against the copper plate on the side jig. This eliminates the indentations of the electrodes on the outside sheet.

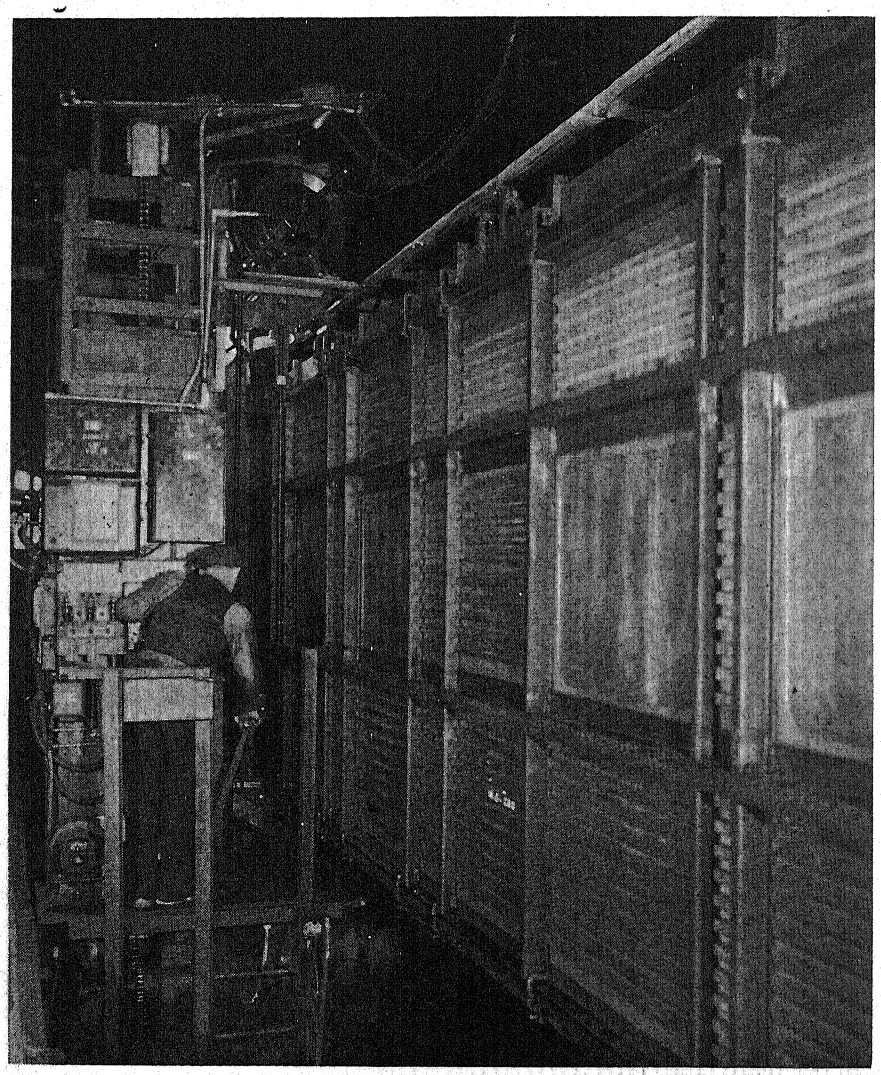


Fig. 7—Spot Welding Framing to Side Sheet with Side Machine

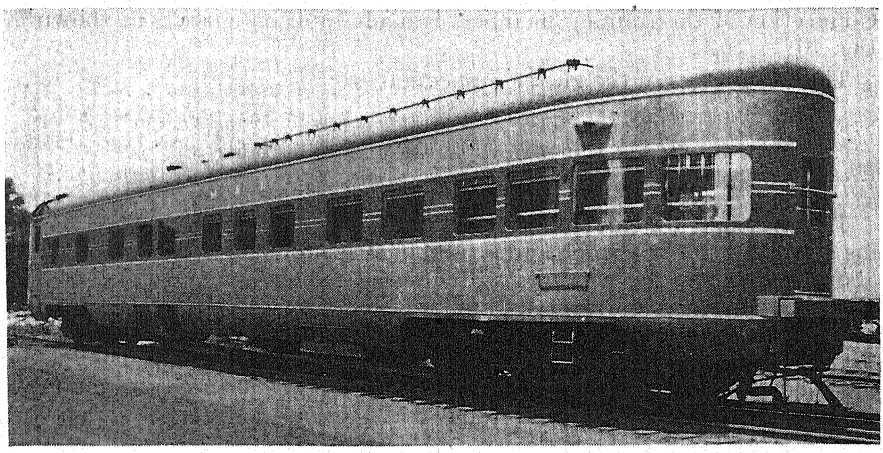


Fig. 8—Completed Girder Type Car

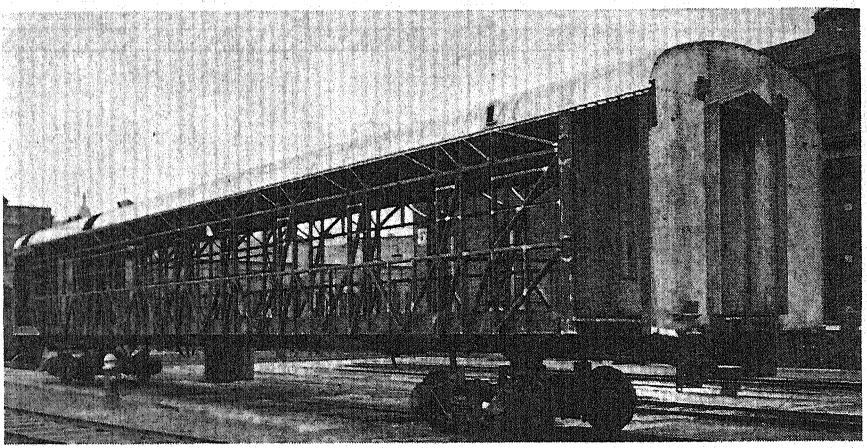


Fig. 9—Car with Truss Frame Sides

A spray of water surrounds each electrode to prevent the heat of the welding from expanding the framing members. If the frame were allowed to expand, it would be spot welded in this condition and would result in buckling of the side sheets.

A completed car is shown in Fig. 8. Note the smooth flush sides.

Truss Side Frame

The truss side frame has been developed on the basis that all the framing members can be so placed and so proportioned that they are uniformly stressed throughout the complete area of their sections. Very thin side sheets can be applied which do not have to withstand any stresses.

A view of a car side having the truss frame construction is shown in Fig. 9.

Connection of the framing members is made by using gussets as shown in Fig. 10.

The advantages of the gusset connection are:

1. Easy fitting for arc welding.
2. Even distribution of stress from one member to the other.
3. All fillet welding.

The sheathing for this side frame is made of stainless steel. The sheathing is made on a drawbench and is used in strips full length of the car, both above and below the windows with pressed panels in between windows. The sheathing runs horizontally and is fastened to the auxiliary members of the truss with bolts, having lock nuts secured to the framing members. The design and application of the sheathing will permit any one piece being removed and replaced without disturbing other sections or the inside finish of the car. A completed truss frame car is shown in Fig. 11.

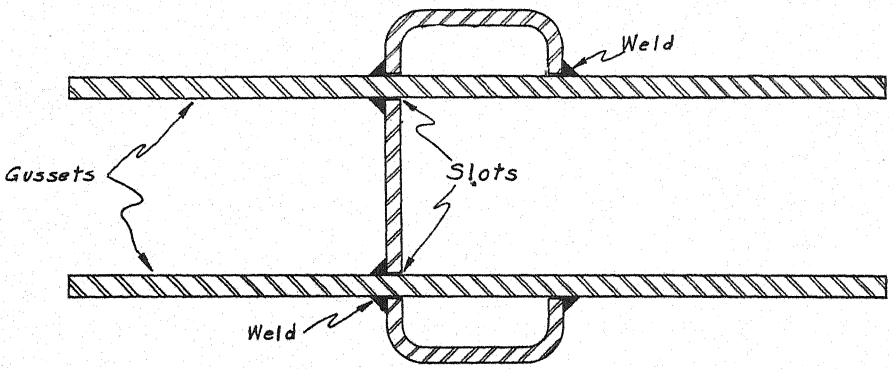


Fig. 10—Cross-Section of Post or Diagonal Showing Method of Welding to Gussets

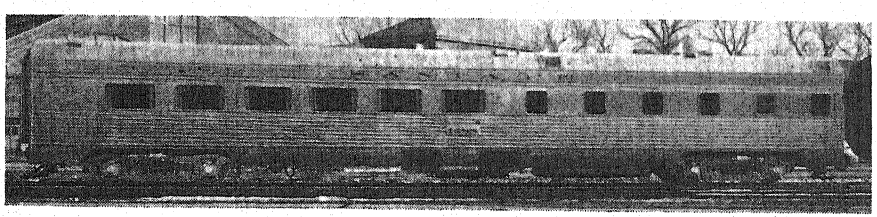


Fig. 11—Completed Truss Frame Car

Underframe

The underframe of the cars is entirely of arc-welded construction. The center sill consists of two rolled shapes welded together. The cross members are welded together in subassembly and then attached to the center sill to form the underframe.

Roofs

Roofs for the car are spot welded on a special jig built full length of the car. The cross supports of the roof, called carlines, are clamped firmly to copper-faced supports which have the same shape as the carline. Roof sheets butt together on these carlines and are spot welded to the carline.

Each roof sheet is reinforced by Z-stiffeners that are spot welded to the sheets in subassembly. The roof spot-welding machine operates on the series principle.

The electrodes are rolls. The two rolls run side by side about one inch apart. They straddle the butt joint of the roof sheets on the carline.

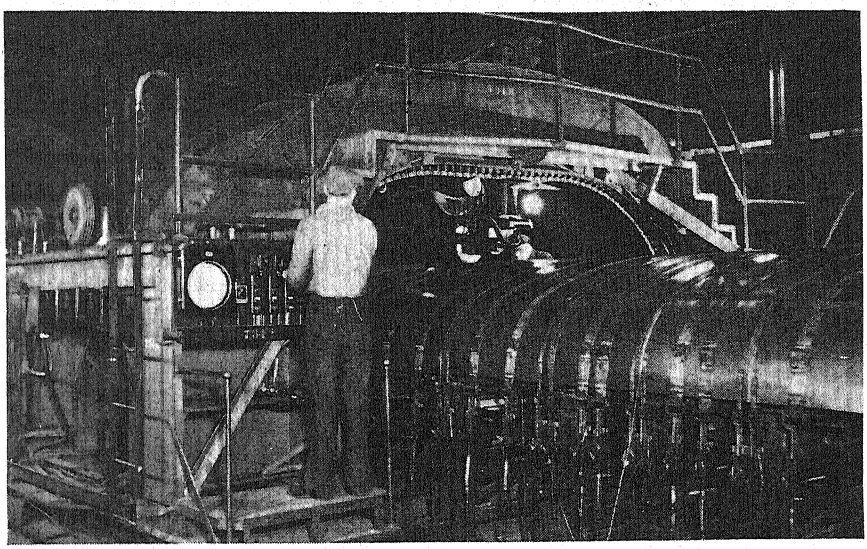


Fig. 12—Spot Welding with Roof Machine

The welding current goes through the sheet and carline from the electrode to the copper back up and up through the carline and sheet to the other electrode roll, thereby making two welds at one time.

A view of the roof machine is shown in Fig. 12.

WELDED BOX CAR

All-Welded Box Cars

The 50-ton 40-ft. 6-in. box cars built in 1939–40 at the shops of the Chicago, Milwaukee, St. Paul & Pacific R.R. Co. involved some new and interesting features not found in other similar cars. These cars were of the all-welded lightweight type, built almost entirely of low alloy high-tensile

steel. The center fillers and striking castings were notable exceptions to previous standard practices, inasmuch as they were of a lightweight design and secured to the center sill solely by welding. The sides consisted of sheets and posts spot welded together but riveted to the side sills which were standard 8-in. channels. The safety appliances, brake rigging and a few minor parts were fastened with rivets or bolts.

Welding Details

Center sills were fabricated by welding together two A.A.R. Z-type sections weighing 33.7 lb. per foot made of special composition low alloy steel The striking castings, Fig. 13, and center fillers were attached to the center sill by 135 in. and 238 in. of $^3/_8$-in. fillet welds, respectively. All-position reverse polarity electrodes were used. After the castings had been welded, the assembly was transferred to a jig where the side sills, underframe members, floor supports and brackets were attached. Crossties were pressed channels and the floor supports pressed Z-bars. Bolsters and cross bearers were welded to the side and center sills by fillets along the web plates and butt welds on the cover plates. The nearly completed underframe was then turned over and welds on the top side made. A bolster reinforcing plate was applied to assist in distributing heavy service stresses which localize in this region.

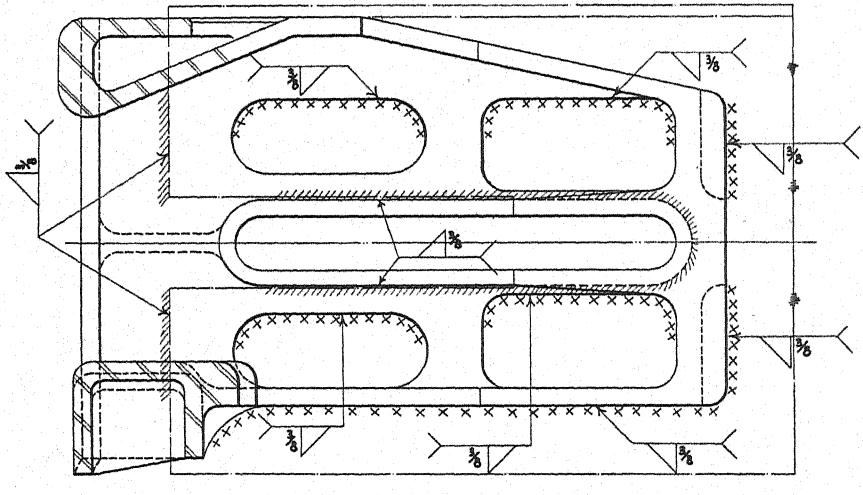


Fig. 13—Striking Casting

Sides

The car sides were made from 15 gage sheets, 21 in. wide, with a 5-in bump on one edge, Fig. 14. In making a side, two identical units were fabricated by omitting the door section of the upper side sill element and cutting the top plate in half at the center of the door span. The bottom side sheet was spot welded to the upper side sill element separately. A side

unit with these parts already welded was then assembled and tacked together on a series spot welder. From here the assembly went to a hydromatic welder where spots were made at 2-in. intervals along each side of the bump. A second series of welding heads on this machine was used to spot the posts to the side sheets. The section was thus completed in a single pass through the welding machine. Posts were zees pressed from low alloy high-tensile steel. Approximately 5600 spots were required for the bump seams, 1700 for the posts and about 900 others for tacking and welding the spark strips.

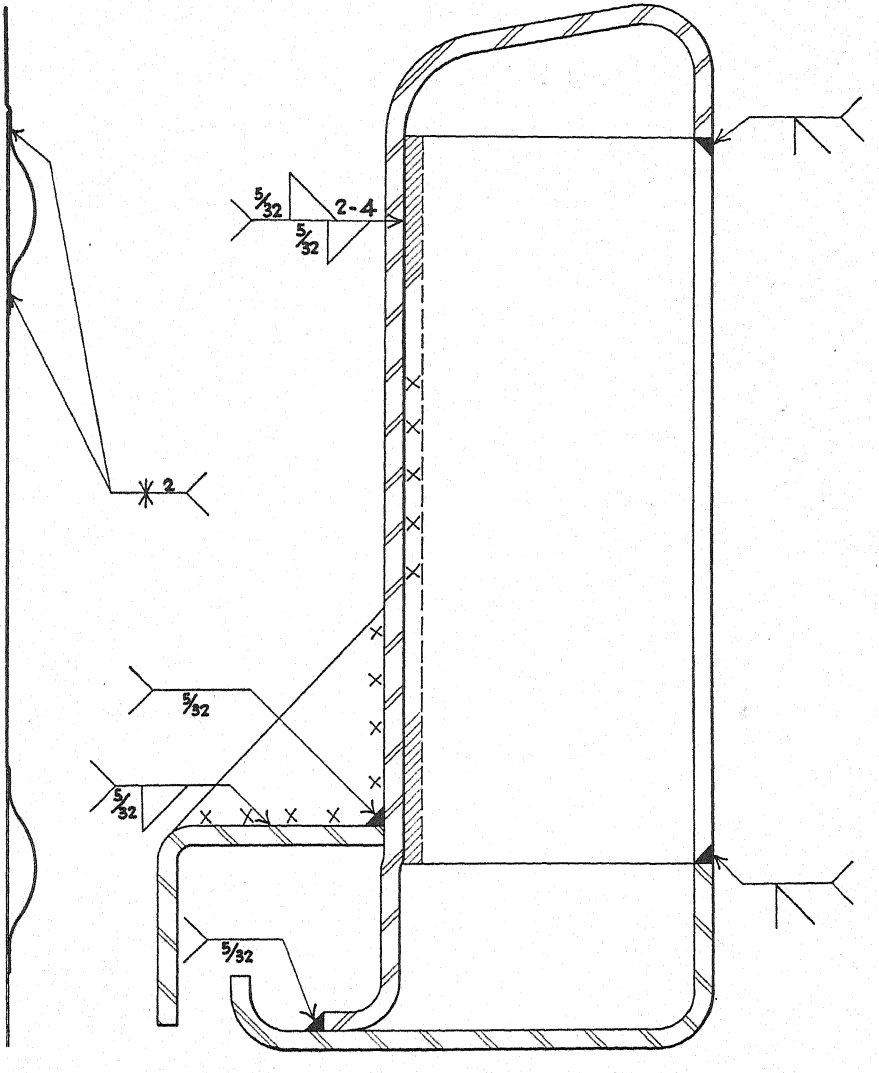


Fig. 14—Side Sheet Arrangement

Fig. 15—Door Hood and Header

In assembling the sides, the ends of the top plate were fitted together in the doorway and a zeebar pressing placed over the joint for reinforcing and as a backup strip for welding. The missing section of side sill was spliced in with butt welds. A channel placed diagonally and a flat triangular gusset were welded to the sides at the bottom of the doorway to reenforce this area. Posts were arc welded to the upper side sill element. The side was then turned over and the door frame with spark strip applied and welded. The door hood with its supporting gussets was welded to the side plate, Fig. 15. Finally, the opening at the end of each bump was closed by cutting out a small vee, hammering the edges together and welding to make the joint weatherproof.

Ends

Ends were made by welding together in a jig two corrugated pressings of $^3/_{16}$-in. steel. A poor joint was formed in the flanged portion on account of distortion in pressing. This part of the splice was made as a vertical weld, using a curved backup strip to close the opening. The corner caps and lumber door in the *A* end were fitted and welded in the same jig. The end was then turned over and the end posts welded on the inside with $1^1/_2$-in. welds where contact was made with the corrugations. On the outside the post was fastened with a continuous fillet along the flanged edge, Fig. 16.

Roofs

The roofs consisted of 13 pressed panels of 14 gage galvanized steel, each section covering the full width of the car. As each section was assembled

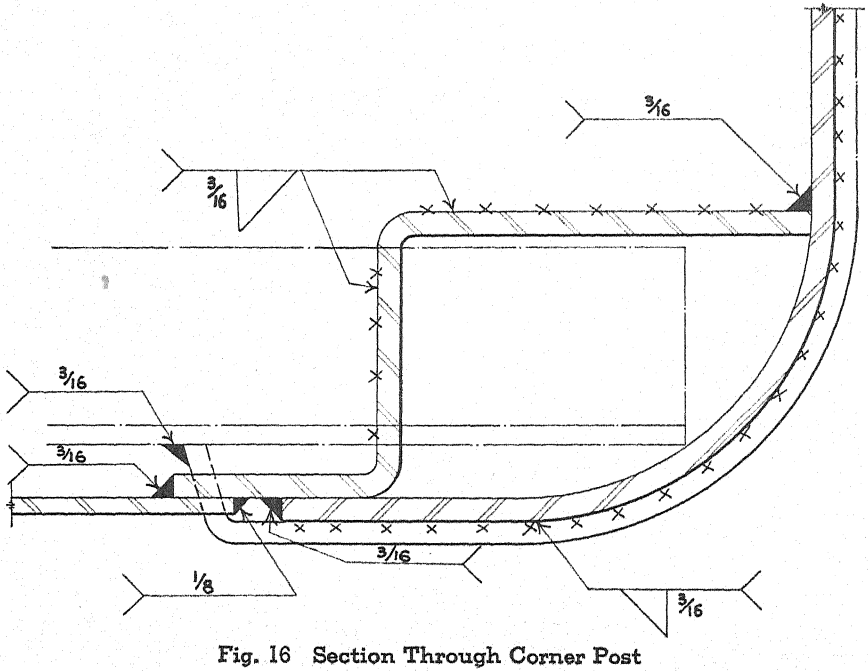


Fig. 16 Section Through Corner Post

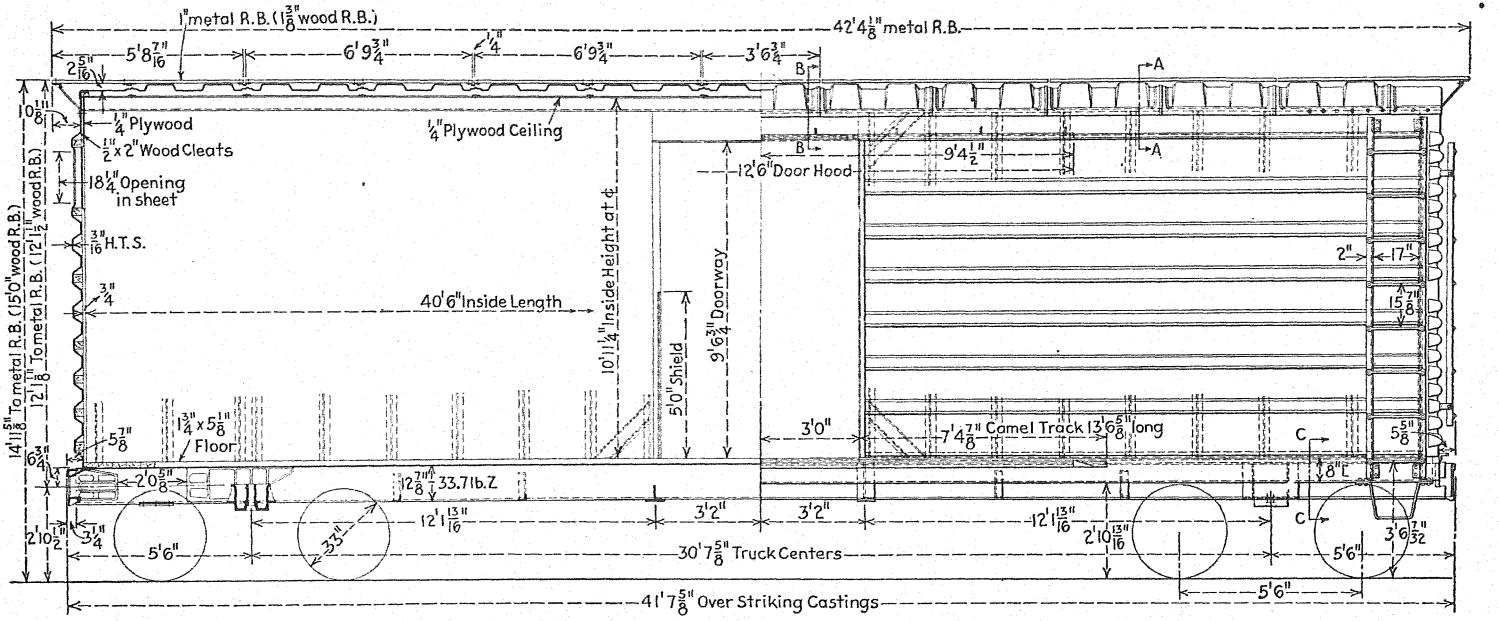


Fig. 17—General Arrangement of Parts, Welded Box Car

in the roof jig, the adjoining edges were drawn together with clamping bars and the seam welded. Offsets were provided near the peak to provide recesses for welding the running board brackets. No protective material was applied to the welded joints except box car paint, but care was taken to clean the joints thoroughly before painting.

Assembly

The completed underframe in its normal position was moved from its jig to temporary trucks on the erection track. The sides, with doors attached, were secured in position with tie rods and temporary bolts. Then the ends were placed and adjusted with push-pull tie rods. Sides were lap welded to the end posts in a single pass except across the bumps where two passes were required. A straight polarity electrode was used and welding was "vertical down." The upper side sill element was fastened to the side sill with rivets, except at the door where it was plug welded. The door track, which consisted of an angle with several brackets, was welded to the side sill. The roof was then set on the car and drawn into position. End corners were fitted and welded and the flanged edge fastened entirely around the car by means of plug welding $^1/_2$-in. diameter holes. Figure 17 shows the general arrangement of the various parts.

Welded and Riveted Cars

Sufficient information is not available to make a direct comparison between a welded and riveted car of the same type, but approximately two tons dead weight were saved by welding the Milwaukee cars instead of riveting.

Welding details are as follows: welding footage, 1200; pounds of electrode per car, 177; pounds of electrode per foot, 0.147; pounds of electrode per hour, 2.72; feet of welding per pound of electrode, 6.8; welding hours per car, 65; feet of welding per hour, 18.5.

RESISTANCE WELDING OF FREIGHT CARS

The demand today by the railroads for lightweight equipment is met through the use of lighter gage, low alloy, high-tensile steel.

Alloy steel, being somewhat more expensive than ordinary mild steel, has certain controlling reasons for its utilization. In many cases reduction in weight without loss of strength, in others increase of strength without change of weight, and in still others increased corrosion resistance recommend low alloy steels to the car designer.

Conditions surrounding car designs with these new materials favor fabrication by welding rather than by riveting. Welding permits the designer to use reduced thickness of low alloy sheets and strips thereby reducing weight without sacrificing strength after due attention is given to more exact stress analysis and design with a view to obtaining the full benefit of the superior properties possessed by the alloy steels. Except for the center sill, the framework is composed largely of pressed steel formed from alloy sheets.

In fabricating the major units of welded box cars such as the roofs and sides, the resistance spot welding is performed by special multiple spot-welding machines.

This development in multiple spot-welding equipment, through the use

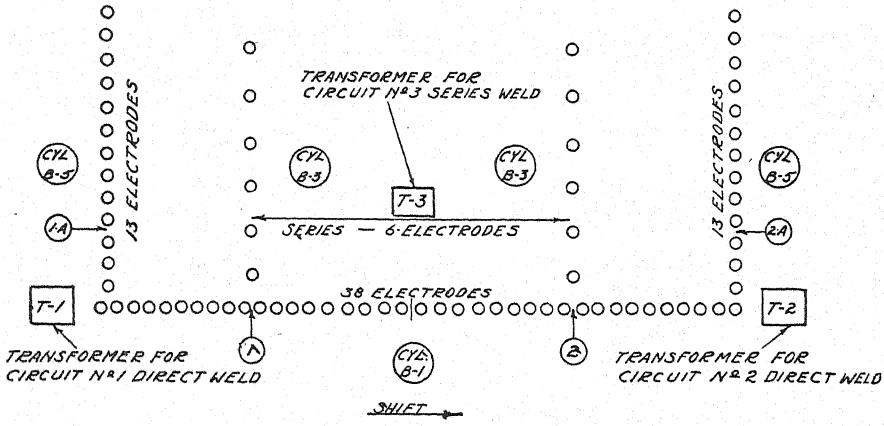
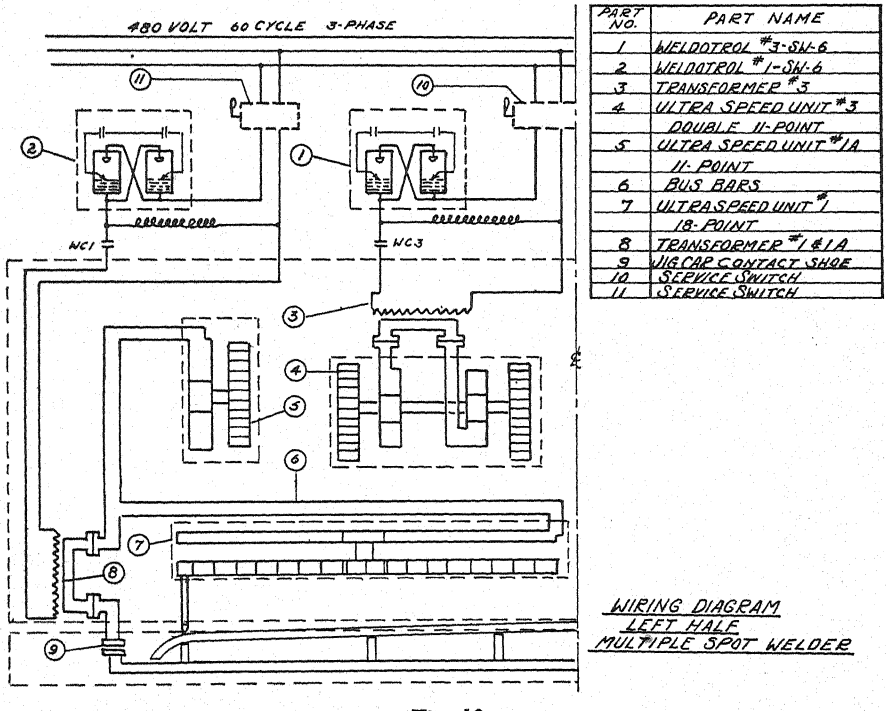


Fig. 18—Diagram of Electrode Locations, Box Car Roof



PART NO.	PART NAME
1	WELDOTROL #3-SW-6
2	WELDOTROL #1-SW-6
3	TRANSFORMER #3
4	ULTRA SPEED UNIT #3 DOUBLE 11-POINT
5	ULTRA SPEED UNIT #1A 11-POINT
6	BUS BARS
7	ULTRA SPEED UNIT #1 18-POINT
8	TRANSFORMER #1 & 1A
9	JIG CAR CONTACT SHOE
10	SERVICE SWITCH
11	SERVICE SWITCH

Fig. 19

of a multiple distributing switch in the secondary or heat generating circuit, permits the entire group of electrodes to be put under pressure simultaneously. These electrodes act as a self-contained clamp at each and every weld location. They remain in that position through the entire cycle of individual electrode welding sequence. The facilities for applying the correct amount of pressure on all electrodes simultaneously and having them dwell (without time delay) until the various welds are sufficiently cool produce a very clean, strong joint of uniform quality (Figs. 18 and 19).

A multiple spot welder is made up of the following principal elements:

1. A constant pressure hydraulic system, for platen lift and electrode shift.
2. An adjustable pressure hydraulic system, as supply to all electrode cylinders.
3. Multiple mounted transformer units as supply to multiple electrode groups.
4. Primary current supply to each transformer group through ignitron contactor and mechanical timing cams.
5. High-speed secondary distributing switches.
6. An indexing welding jig car covered with a secondary copper top.
7. A water-cooling system to transformers, secondary switches, distributing cable and electrodes.

These automatic multiple welding machines consist of an (upper moving) platen, upon which is mounted the multiple electrode setup adapted to roofs (Fig. 20), and a second setup for sides (Fig. 21).

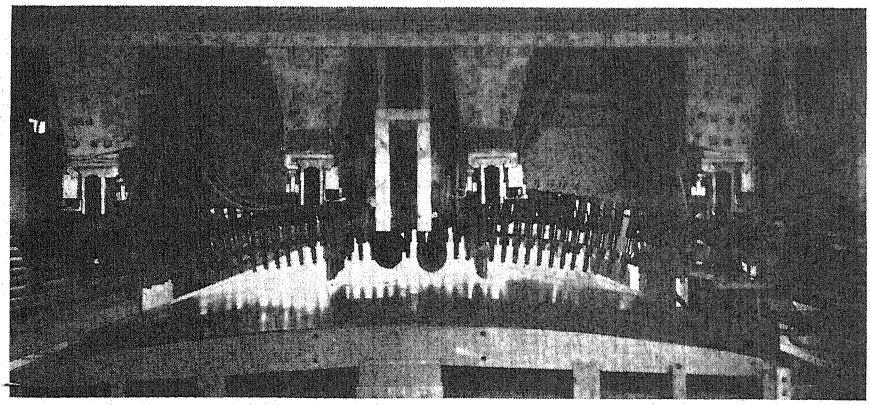


Fig. 20—Box Car Roof on Jig Car Under Electrode Setup

The panel welder for roofs has two alternating welding jig cars which move on a track under the electrode platen and permit a continuous operation of the roof panel welder, roof after roof. The alternate jig car is loaded with roof frames and roof sheets by the fitters and moves into the welder as soon as the other jig car vacates the welding position.

Preliminary to the spot-welding operations, the roof-framing and side-framing members are assembled in an accurate jig and firmly clamped into position. In the case of the roof, the carlines are arc welded to the side

plate and the purlines to the carlines; with the side-framing members the posts are arc welded to the side sill angle and the side plate.

The roof-framing unit is then placed on the welding jig car secondary copper grillage which backs up the setup of multiple electrodes. The roof sheets are fitted and clamped in position for spot welding.

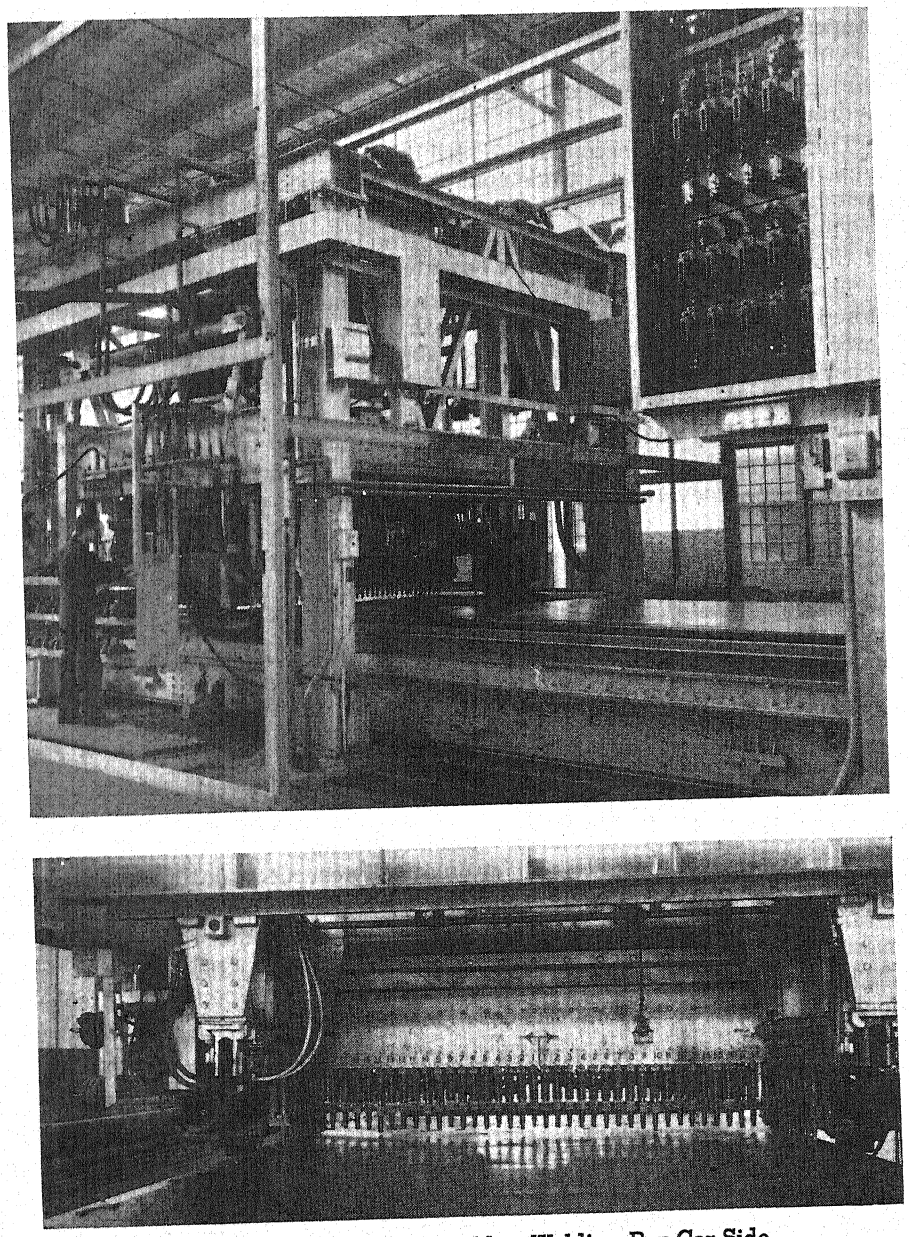


Fig. 21—Multiple Spot Welder, Welding Box Car Side

The motor-driven jig car through its push-button magnetic control is indexed to the panel to be spot welded.

The platen, with a setup of the required number of electrodes, is lowered to contact the work through a push button magnetically operated control valve from a constant pressure hydraulic system. At the same time, the contact shoes of the direct welding transformers make contact with the copper bus bar grillage on each side of the welding jig car.

All of the electrode cylinders are put under pressure simultaneously through manually operated valves and supply from an adjustable pressure hydraulic system.

The motor-driven secondary distributing switches pass about 20,000 amp. to each welding electrode connected to respective segments of these switches.

These switches are started by push button and stopped by a limit switch at the end of their travel and are operated both forward and backward.

Three secondary switches are operated simultaneously on three-phase closed delta primary power supply with three welding transformers and three ignitron contactors available to supply current. In this manner, a panel of 70 to 80 spot welds may be divided and made in one-half the time that would otherwise be required.

Two secondary switches are operated consecutively to segregate a group of about 32 spots in sequence of 19 and 13 spots, respectively.

No. 3 secondary switch is operated two welds at a time as in series spot welding.

Adjustable timing cams operate the microswitch attached to the trolley of each secondary distributing switch and determine the desired timing of each spot.

Intermediate spacing of spots requires 1-in. lift of the platen and a 1-in. and 2-in. shift of the electrode mounting and shifting slide. The panel cycle is then repeated as required to meet the spacing required.

When the panel cycle is completed, the platen is raised 4 in. and the jig car is indexed to the next panel.

More than a dozen push buttons and more than a dozen manual valves are assembled on a central operator's control board. Manually, these individual controls initiate any one of a dozen operations. The manual setting of a selector switch, however, will automatically execute a dozen operations as one. Duplicate panels may thus be spot welded with dispatch.

Magnetic control through a sequence panel is the brain or nerve center making possible the several functions in the execution of a panel cycle.

The push buttons, selector switch, limit switches, contactors and solenoids are interconnected with the entire machine setup to:

1. Permit manual control of each welding operation individually if desired.
2. Permit a setup to be made, which will then proceed automatically to the final pre-set point.
3. Permit any previously pre-set setup to be interrupted if desired, a single operation performed and then continue the pre-set setup.
4. Permit manual termination of any individual operation.

The setup for panel welding of car roofs of a given design utilizes three

transformers, five secondary switches and 76 electrodes, arranged in five groups; two groups of 19 electrodes each take the crossline or carline welds; two groups of 13 electrodes each at right angles take the side plate welds; a fifth group of 12 electrodes also at right angles to the first two groups take the purlin welds between the carlines.

These 76 electrodes are attached to the spot-welder platen through pedestal mountings and shifting slides which permit 76 or 152 additional spot welds to be made by a 1-in. vertical lift of the platen and a 1-in. and 2-in. lateral shift movement of the various groups of electrodes. For each electrode group the shift is parallel to the mounting.

It is to be remembered that the copper grillage on the welding jig car backs up the electrode pressure required for welding and distributes the low-voltage high-amperage current to these electrodes.

The system of fabrication by welding of underframes, sides, roofs and ends of freight cars in jigs apart from the main track assembly permits positioning for horizontal welding when required and accessibility for careful work and inspection.

The final assembly by rivets of these main subassemblies in track production lines facilitates the desired output and insures economic repairs at some future date.



Fig. 22—Car Manufactured by This System

Four hundred box cars of 50-ton capacity have been built of alloy steel and welded construction (Fig. 22).

The saving in weight is approximately 4 tons per car as compared with A.A.R. riveted steel cars.

REPAIRING WELDED STAINLESS STEEL PASSENGER CARS

The streamlined passenger cars referred to in this chapter are all welded and practically all stainless steel. They are almost entirely welded by a

controlled low-cycle, alternating current, spot-welding process. However a certain amount of electric arc welding is employed to join stainless steel to certain mild or low alloy steel members, and there is frequent use of soldering at roof joints and along catwalks.

Originally the power car of this type had an entirely welded front end and sides with the pilot also welded, but these have been replaced with bolted outer or cover sheets to facilitate quick removal, repairs and replacement.

In this type of car the stainless steel sheets range in thickness from 0.020 to 0.075 in. except for center sills, pilot and front end sheets which are as thick as $^3/_{16}$ in.

There have been very few failures in welds, the repairs done on this equipment being due mainly to accidents such as striking objects while in motion or being sideswiped by other railroad equipment.

The most frequent damage is to the front end, especially the pilot; however, the sideswiping is the most difficult and costly to repair, and there have been a few cases of rear end damage.

The stainless steel used is within the 18–8 range with no stabilizing agents added, and the bulk is on the low side of the range or approximately 17–7. Steels with strengths of from 120,000 to 150,000 psi. are used.

The types of damage encountered include dented, twisted, crushed and torn sheets and shapes, and the pulling of the spot weld areas out of one or the other sheets.

Most of the twisted and bent sections can be straightened by hammering or rolling after removing them from the structure by chiseling between the sheets to cut the spot welds.

Torn sheets in many cases are straightened, electric arc welded, ground and polished more rapidly and more economically than a new sheet can be made, especially on irregularly shaped sections.

In the case of electric arc welding a stainless steel coated electrode is used with a chill block or water quench on the reverse side, whenever possible, in order to minimize warpage.

Arc-welding machines should be of a type that have excellent stability at low current ranges.

The thinner sheets are more difficult to weld, and it will be found an advantage to remove the coating on an electrode, lay it on the junction of the pieces to be joined, and then arc weld to the bare electrode instead of to the joint ends.

To remove dents on the heavier sections a pad of weld metal is built up at the bottom of the dent, making the pad about $^1/_4$ in. thick, then a steel bolt shank is welded to the applied pad, with the thread ends projecting well up beyond the normal surface line of the sheet. The strongback method is then applied while the dented section is raised in temperature to about 900°F. The pad is built up so as not to alloy the stainless steel sheet where the plain steel bolt is welded on. After the sheet is pulled in place, the pad material is sawed to remove the bolt and mixed metal, and the balance of the welded pad is ground off and the sheet is then polished.

In making lap joints on thin sheets or shapes where a strong and sound joint is desired, it is good practice to use silver solder (melting point

1170°F.) and a suitable flux. When doing so, the usual precautions common to the use of fluoride fluxes should be observed. Also, when using this method, care is taken not to overheat the stainless steel as the flux is then rendered useless and a poor joint may result.

The greatest difficulty in making repairs with the "shot" welding process is that it is necessary to place the electrodes on both sides of the object to be welded. In this type of construction the welds must be made in a prearranged sequence. After certain portions are completed it is difficult and costly to "back track" and make additional welds.

In the repairing of completed cars in low stress locations, it is not always advisable in view of additional cost, to use the standard "shot" welding procedure, and in such cases the "poke" welding procedure is often permitted. A "poke" weld is made by grounding the structure in a convenient location by placing one terminal in as close proximity to the proposed weld as is consistent. The other terminal is attached to a copper bar with an electrode welded on the adjacent end. This is pressed against the spot to be poke welded and the current is turned on the "shot"-welding machine in the usual way. This procedure has great economic advantage, and can be used with a good degree of certainty when proper preparations are made. It has been found that a light center punch mark on the outer sheet will greatly improve the certainty and strength of a "poke" weld.

Where true "shot" welds must be made in locations where it is impossible to use standard tools, it is possible to make special shapes of copper bar arms to reach such locations, and it is advisable to carry a stock of copper bars for this purpose whenever a repair job is at hand.

Stainless steel does not cut readily with the oxygen cutting process. It can be severed by melting. A carburizing or reducing flame is preferred for this operation. Members which are to be fitted for welding should be trimmed by sawing, grinding or shearing.

GENERAL WELDING PRACTICE ON LOCOMOTIVE BOILERS AND TENDERS

Locomotive Boilers

Scope.—Fusion welding is used to a considerable extent in practically all locomotive boiler construction and has universal application in the construction, replacement and repair of fireboxes.

Materials and Process.—The steel plates are of firebox or flange quality conforming generally to standard specifications for such materials and in some instances modified slightly in accordance with the using railroad company's specifications. Some low alloy and other special materials are in experimental use for firebox plates. The arc process is used for the bulk of boiler welding although the oxyacetylene process is sometimes used in repair work, the choice depending largely on the equipment available. The majority of the railroads use medium or heavy coated electrodes, some use thinly coated electrodes and still others use bare rod. Use of the heavy coated electrodes is increasing and has served to enhance confidence in the welding process.

Codes.—There is no code that is generally applicable to welding on locomotive boilers. Such a code is being prepared by the A.S.M.E. Boiler Code Committee. None of the boiler welds made by the railroads are subjected to radiographic examination and stress relief and no special tests are made of completed welds. Each common carrier railroad is primarily responsible under the terms of the Federal Locomotive Inspection Law, which is administered by the Bureau of Locomotive Inspection of the Interstate Commerce Commission, for the design, construction and maintenance of any locomotive used on its line. In conformance with this responsibility each major railroad has issued its own instructions and practices governing welding operations which results in some differences in practices as between the various railroads. The instructions and practices of individual railroads are subject to change as experience is acquired with materials, techniques and service performance. The Bureau of Locomotive Inspection has not issued any formal rules on boiler welding but it does control welding applications and other practices upon which it has not issued specific rules under authority of condition and suitability for service provisions contained in the law.

Design Considerations.—Use of welding on boilers of conventional type locomotives has not resulted in any changes in design other than the change from riveted to welded joints, since, except for changes in size and proportions, these boilers have become practically standardized because of limiting conditions incident to the service.

Economics or Advantages.—Due to wide differences in the facilities and equipment in railroad shops no generally applicable statistics from which comparisons of cost of welding vs. riveting in locomotive boiler construction and repair are obtainable. However, the use of welding has effected large reductions in cost of repairs, with further vast economies in operation because of the elimination of leakage at the joints in fireboxes with consequent less time out of service undergoing repairs, which, in turn, has been one of the factors contributing to improved locomotive performance, more intensive use and longer locomotive runs.

Fireboxes

Firebox Construction.—Lap joints, many of which were welded on the fire side only, were at one time used to a considerable extent. In later practice butt joints are used in practically all welds in fireboxes. In new construction, and in repairs where practicable, all joints, except that at the door hole flange, are welded from both the fire and the water sides; single vee welds are applied on the fire side after which a groove is chipped out of the water side of sufficient depth to remove all flaws, and welding applied in the groove.

In the best type of construction and repairs the skirts of the flanges of the flue and door sheets are made sufficiently wide to receive one row of staybolts, thus bringing all welded joints, except that at the fire door hole flange, between two rows of staybolts; in some constructions the flanges of the flue and door sheets have short skirts not supported by staybolts.

Figure 23 shows a typical completely welded firebox and combustion chamber with a one-piece crown sheet. In some constructions the crown sheet is in two pieces with a transverse weld joining the section comprising

the top of the combustion chamber with that over the firebox. Another variation makes use of a continuous sheet for the sides and crown. Some railroads rivet the crown sheet to the flue and door sheets and the joints, after calking, are seal welded in some instances. The longitudinal welds joining the crown and side sheets are generally placed from 12 to 15 in. below the highest part of the crown sheet to protect the joints from overheating in the event of low water.

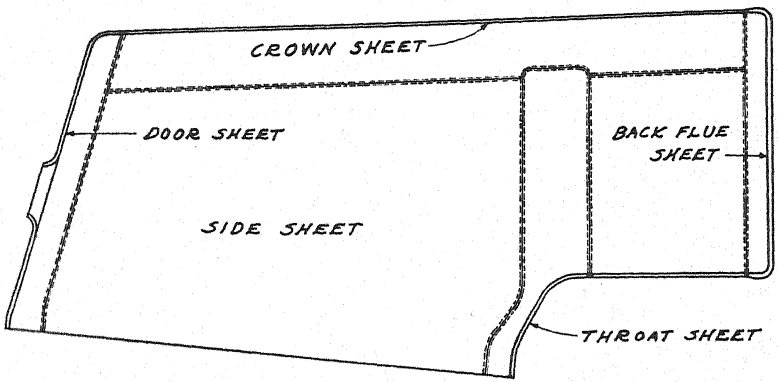


Fig. 23—Typical Welded Firebox

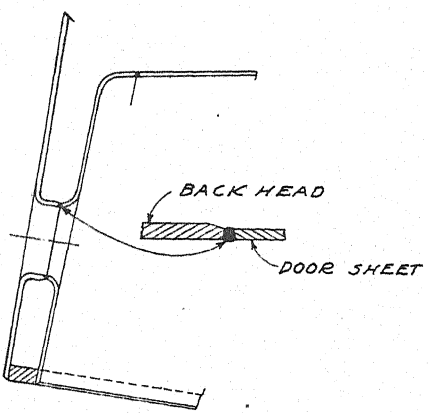


Fig. 24—Typical Method of Joining Door Hole Flanges

Firebox Door.—Figure 24 shows the firebox door hole flange of the door sheet butt welded to the corresponding flange of the back head. Another method for forming this joint is to lap the flanges and apply a fillet weld around the circumference. The first method is generally preferred.

Tubes and Flues.—After the fire tubes and superheater flues are applied

in the firebox flue sheet in the conventional manner by prossering, rolling and beading, the beads are usually seal welded as shown in Fig. 25.

Thermic Syphons.—Double-welded butt joints are generally used for attachment of the flanges of syphons to the crown sheet except in instances where the installation is made in existing fireboxes in which event single-vee welds are sometimes used with the welding applied from the fire side. Fillet welds are used at the neck connection to throat sheet. A conventional installation of syphons in a firebox and combustion chamber is shown in Fig. 26.

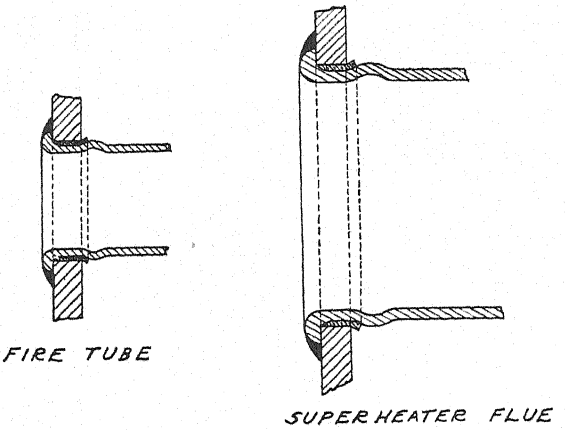


Fig. 25—Seal Welding of Beads of Fire Tubes and Superheater Flues to Back Flue Sheet

Security Circulators.—A conventional installation of circulators in a firebox and combustion chamber is shown in Fig. 27.

Firebox Renewals.—In most instances where the boiler is removed from the frame or where other conditions render the procedure practicable, complete fireboxes are welded as in new construction before insertion in the boiler back end. Completion of the welding before the firebox is inserted in the back end results in a product of maximum strength as the firebox can be turned to permit welding from the most advantageous position and all joints can be welded from both the fire and water sides. In other instances the various sheets are prepared for single-vee butt welding, assembled in the back end, properly aligned with approximately a $^1/_{16}$-in. gap in the root opening, tack welded about every 12 to 15 in., and welded from the fire side. Where accessible, welding is also applied from the water side as in new construction. The first bead is usually applied with a smaller diameter welding rod than the succeeding beads as it is aimed to have the water side of the weld clean and flush with the sheets with no gaps in which mud or sediment may collect. The succeeding layers are then applied to fill the groove and build up a reinforcement of approximately $^1/_{16}$ to $^1/_8$ in.

Renewal of Sheets, Part Sheets and Application of Patches.—Firebox sheets are renewed in whole or in part, or patched, by welding in place sheets of

firebox steel equal in thickness to the section removed. The joints are prepared and welded in the manner described in the foregoing paragraph. All welds should be located midway between two rows of stays and where

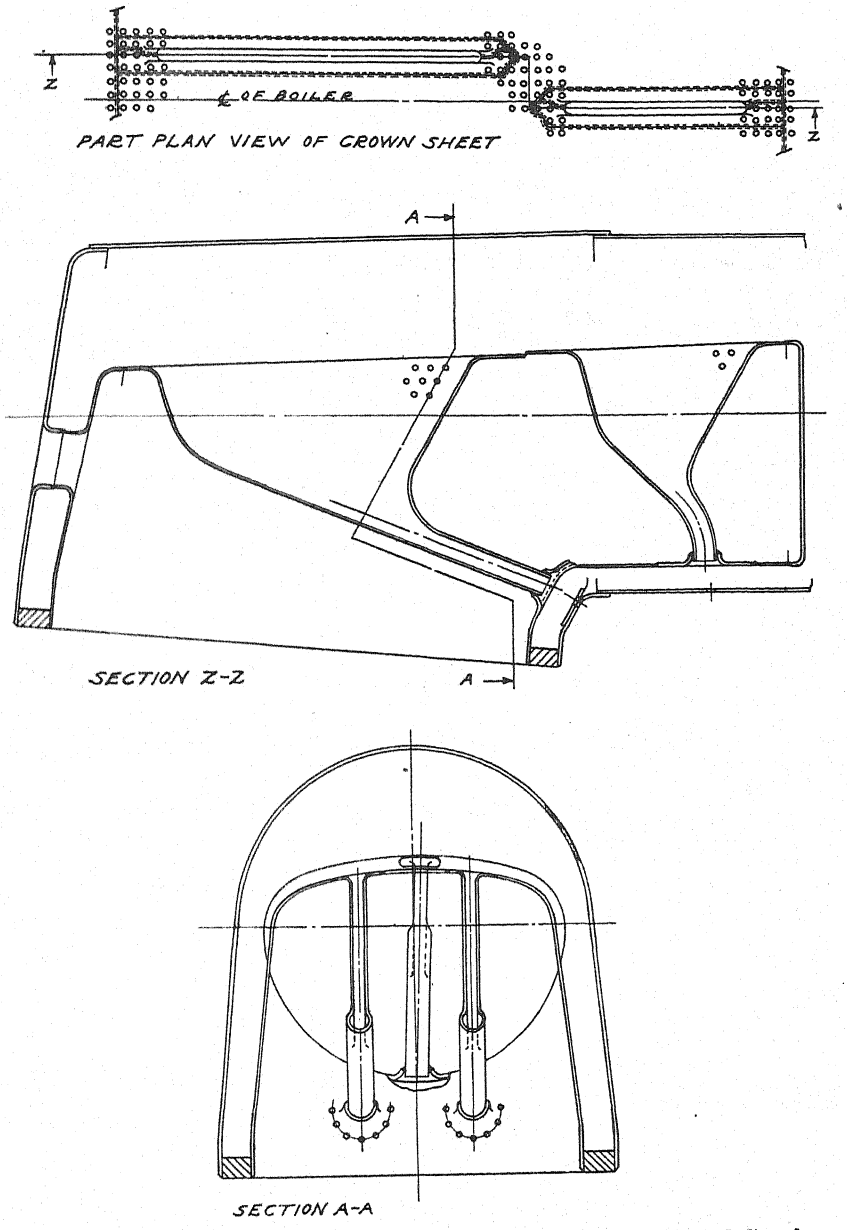


Fig. 26—Conventional Installation of Syphons in a Firebox and Combustion Chamber

possible welding should be applied from both fire and water sides. Side, door and throat sheet patches should not terminate just above the firebox ring as the sheet is often deteriorated adjacent to the top of the ring and a durable repair may not be effected.

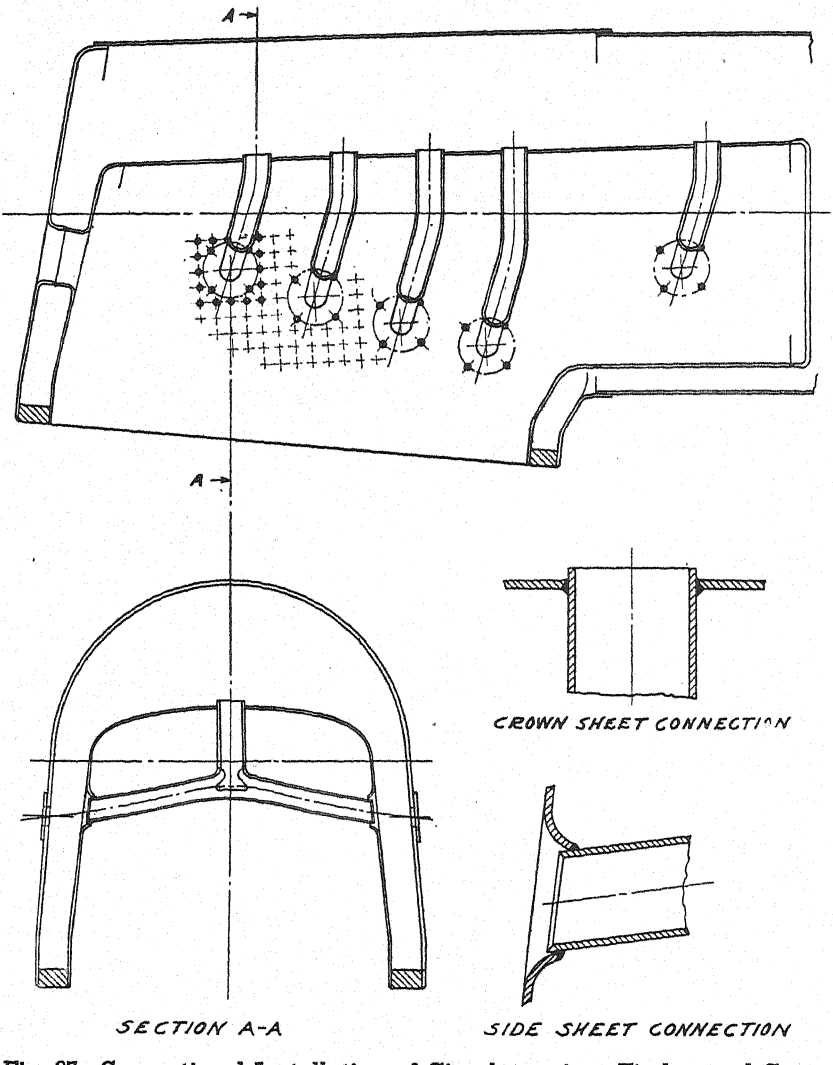


Fig. 27—Conventional Installation of Circulators in a Firebox and Combustion Chamber

Pitting or grooving commonly occurs in back flue sheets across the top knuckle and in the course of time develops into a crack. Repairs are made in some cases by cutting out the defective part, the cut extending down-

ward and crosswise either through the bridges between the flue holes or through the solid sheet between the holes, to take in at least the top row of superheater flues, and a butt-welded patch inserted. In the best practice these patches are welded from both the fire and the water sides. Other defective parts of these sheets are cut out and new sections welded in place; in the application of small patches the welding is sometimes applied from the fire side only to avoid the necessity of removing any considerable number of flues. Various types of repairs are also made to front flue sheets by cutting out portions containing defects and welding in new sections in a manner similar to that followed in the repair of back flue sheets.

Cracks.—Cracks in firebox sheets not extending further than the length of two staybolt pitches are veed out and welded if the base metal is otherwise serviceable. Staybolts, if within the line of welding, are removed and new staybolts applied after completion of the welding. Some of the railroads apply patches to welded cracks at the first opportunity when the locomotives are out of service for repairs. Cracks in front and back flue sheets through the bridges between flue holes and elsewhere are veed out and welded. Cracks in firebox rings and complete breaks are also veed out and welded and new sections are welded in when required.

Boiler Shells

The shells of all conventional type locomotive boilers, other than the experimental welded boiler described hereafter, are of riveted construction and the use of welding is limited to preclude applications on unstayed parts, unless the part to which the welding is applied is supported by other construction that will maintain the required factor of safety, shell courses, domes, drums and hip sheets, and the welding of joints in locations in the firebox casing that are subject to flexure. The principal uses of welding on boiler shells follow.

Seal Welding.—The abutting edges of shell plates of joints having inside and outside butt straps are welded at the ends for tightness as shown in Fig. 28.

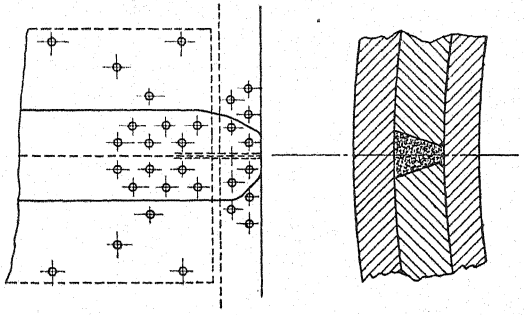


Fig. 28—Seal Welding at End of Butt Straps

The outside and inside firebox sheets are seal welded to the firebox ring at the corners after calking; and seal welding is applied, after calking, to the

joints of the outside side sheets and throat sheet and back head for a distance of from 12 to 20 in. upward from the firebox ring.

Flexible Staybolt and Radial Stay Sleeves and Caps.—Flexible staybolt and radial stay sleeves are welded to the outside firebox sheets, including the roof sheet and combustion chamber shell course; two types of sleeves are shown in Fig. 29 (*a*) and (*b*). Threaded sleeves were previously standard practice. Many of the sleeves applied for radial stays are at a considerable angle from a radial line at the point of application and the screwed sleeves necessarily had very few full threads in the sheet and were therefore subject to leakage; welding these sleeves instead of using screw connections has solved the problem of leakage. With another design of flexible stay, in which the head seats on the boiler shell, the caps are welded to the shell as shown in Fig. 29 (*c*).

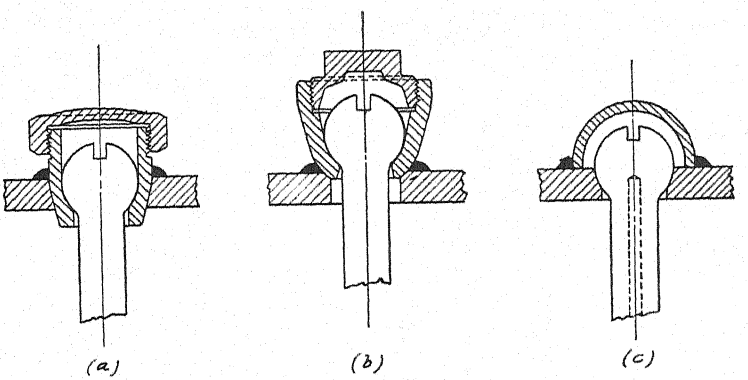


Fig. 29—Welded Staybolt and Radial Stay Sleeves and Cap

Stoker Inlet Openings.—Some stokers discharge coal into the firebox through sleeves in the form of large tubes which extend through the back head and door sheet. The sleeves are commonly made by rolling a sheet of firebox steel to the proper diameter and butt welding the longitudinal joint. The edges of the ends of the sleeves are beaded and welded to the door sheet and back head in a manner similar to that described under tubes and flues.

Patches.—Butt-welded patches are applied to surfaces supported by staybolts of normal spacing in the outside throat sheet, outside side sheets and back head. The bottom weld should be located not lower than the bottom row of staybolts, or the patch may extend to the bottom of the firebox ring and be riveted thereto; the joints of all patches should be midway between two rows of staybolts. Welded patch joints in the side sheets should not be located in or close to any curved surface in the side or roof sheets in order that such welds will not be within the zone of flexure that ordinarily occurs in the roof sheet and upper parts of the side sheets of radial stayed boiler back ends. Welded joints running parallel thereto should not be located in a flange or roll in any location in the firebox casing sheets. Welded joints in the back head inside of the cab or welded joints in the outside side sheets that extend inside of the cab should be covered with a patch.

Cracks.—If the base metal is otherwise serviceable cracks not extending farther than the length of two staybolt pitches in outside side sheets, throat sheets and back heads, within the areas where patches are applied as given in the foregoing paragraph, are veed out and welded in enginehouse repairs to enable the locomotive to run out its assigned mileage between shoppings. Welded cracks on any part inside of the cab, except short radial cracks in the door hole flange, should be covered with a patch as described in the paragraph next above.

Non-Pressure Parts.—Welding is used extensively to form joints in non-pressure parts such as shrouding, steam dome and sand box jacket casings, ash pans and smoke boxes but as these present no problems the operations are not here referred to in detail.

Welded Locomotive Boiler

The development of fusion welding and its application in the construction of shells of power boilers for stationary service have not been paralleled by corresponding extension of welding in the construction of shells of locomotive boilers. The railroad shops do not have the equipment for examination of welds, and heat treatment thereof, that will meet code requirements for power boilers and no practicable means has been advanced for performing repair work on boiler shells since such work, to be assured of equal integrity to that of original welded construction meeting code requirements, would need to be radiographed and stress-relieved.

Interest in fusion welded locomotive boiler construction was first made manifest by the railroads collectively in the year 1935 at which time the Mechanical Division of the Association of American Railroads took action that started a study of the subject by its Committee on Locomotive Construction. Later in that year the Committee was advised by Mr. G. S. Edmonds, Superintendent of Motive Power, Delaware & Hudson Railroad, that he had, in collaboration with the American Locomotive Company and others, been studying and investigating the development of a welded conventional type locomotive boiler for a period of several years and arrangements were thereafter made for joint work on the problem. A Subcommittee appointed by the Committee on Locomotive Construction, Mr. Edmonds, representatives of locomotive builders, the A.S.M.E., and the AMERICAN WELDING SOCIETY, participated in consideration of a design for a welded boiler, and a specification covering construction and subsequent handling for a period of five years and final drawings submitted by Mr. Edmonds were approved by all the foregoing in January 1936.

Mr. Edmonds then presented the specification and design to Mr. John M. Hall, Director, Bureau of Locomotive Inspection, and filed a formal application for approval of the specification and the use of one welded locomotive boiler for the purpose primarily of experimentation, but with the view that when its practicability had been proved welding might be adopted as a standard method of construction. The application contained proposed changes in the rules for inspection and testing with respect to this particular boiler which required more frequent and thorough inspections and tests than are mandatory under the established rules. It was further specified that the boiler would be tested in actual operation for a period of six weeks as a stationary boiler before use on a locomotive in road service.

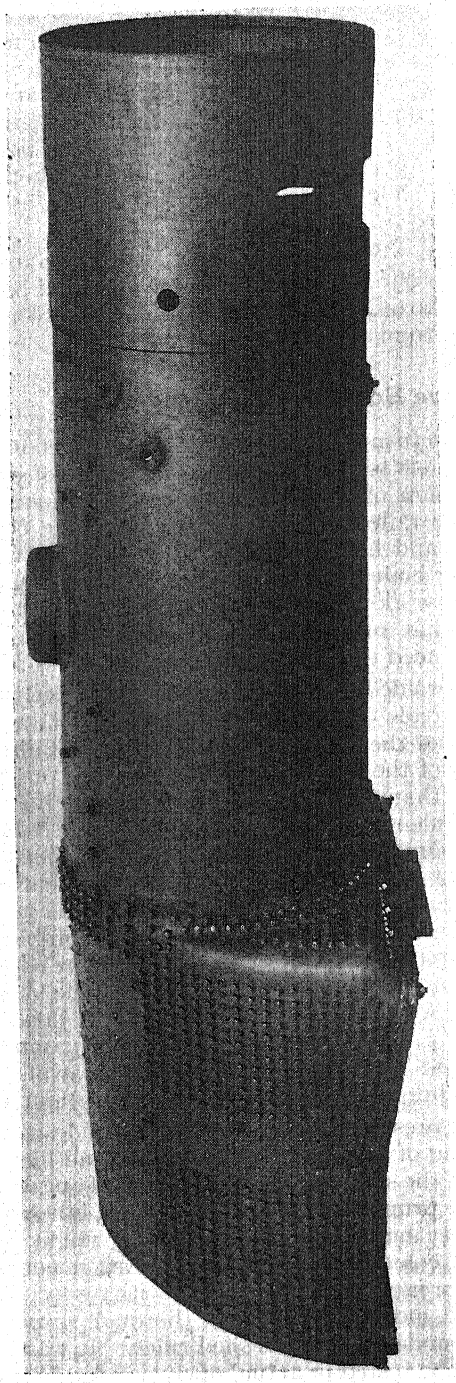


Fig. 30—Welded Locomotive Boiler

This was the first application for use of a welded boiler that conformed to the procedure required by the Locomotive Inspection Law for changes in the rules to authorize this method of construction. This application was granted after some minor alterations were made in the specification and drawings and the project approved by the General Committee of the Mechanical Division, Association of American Railroads.

The boiler was built by the American Locomotive Company; the tensile strength of the steel plates was 55,000–65,000 psi., with maximum carbon content 0.25%. All welding complied with the A.S.M.E. Power Boiler Code requirements. A photograph of the boiler is shown in Fig. 30 and a diagrammatic sketch illustrating the location of the principal welds is shown in Fig. 31.

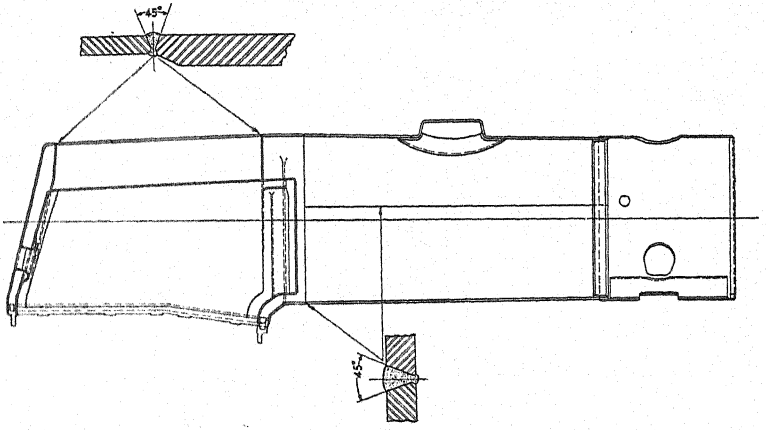


Fig. 31—Welded Boiler

Tests of the welded specimens showed the following results:

> Tensile test piece broke through the base metal at approximately 60,000 psi.
> The all-weld-metal specimen showed a yield point of more than 50,000 psi. and an ultimate strength of more than 60,000 psi. with an elongation of 30%.
> The free bend specimen showed an elongation in the weld metal of 33%.

The barrel portion of this boiler is conical in shape, 88 in. outside diameter at the smokebox end, and 94 in. outside diameter at the firebox end, the plate thickness being $1^1/_{16}$ in., providing a factor of safety of 5 for a working pressure of 225 psi. with an allowable joint efficiency of 90%. The firebox inside is 132 in. long by 114 in. wide, measured at the grate. . The outside firebox wrapper sheet is $^5/_8$ in. thick. The longitudinal and circumferential joints of the boiler shell up to the smokebox are double-welded butt joints.

The dome is 33 in. I.D. flanged from one piece of plate $1^1/_{16}$ in. thick; the bottom flange is fitted into the shell and attached with a double-welded butt weld. The boiler shell is reinforced at this point by a flanged dome liner $1^1/_8$ in. thick which extends up into the dome, being attached to the dome and boiler shell by fillet welds at the edges of the liner. This construction is shown in Fig. 32.

The throat sheet and top connection between the shell and firebox wrapper sheet is integral, having been formed from a plate $1^3/_{16}$ in. thick.

The backhead is $^9/_{16}$ in. thick of normal design, with the flange made sufficiently deep to permit the location of the welded joint between two rows of staybolts.

The front flue sheet is welded to a circular ring which is fitted to the inside of the shell and attached by fillet welds. Welded gusset plates around

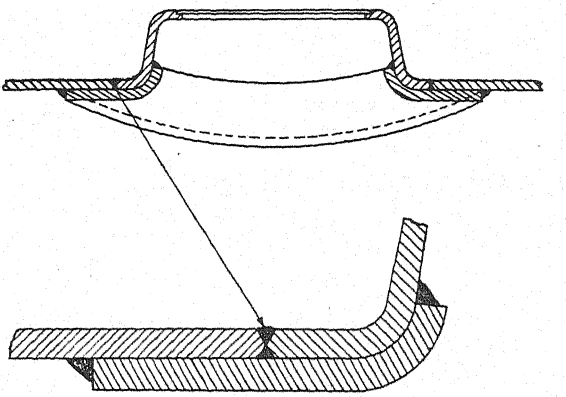


Fig. 32—Dome Reinforcing and Attachment

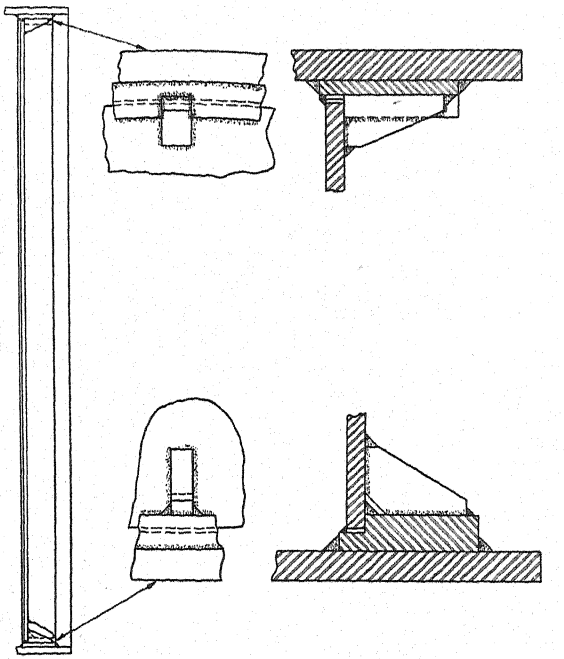


Fig. 33—Front Flue Sheet

the circumference support the sheet from the non-pressure side. This ring is provided with slots at the top and bottom centers so that the flue sheet can be removed and renewed without cutting out any welds except those directly attaching the flue sheet to the circular ring and gusset plates. See Fig. 33.

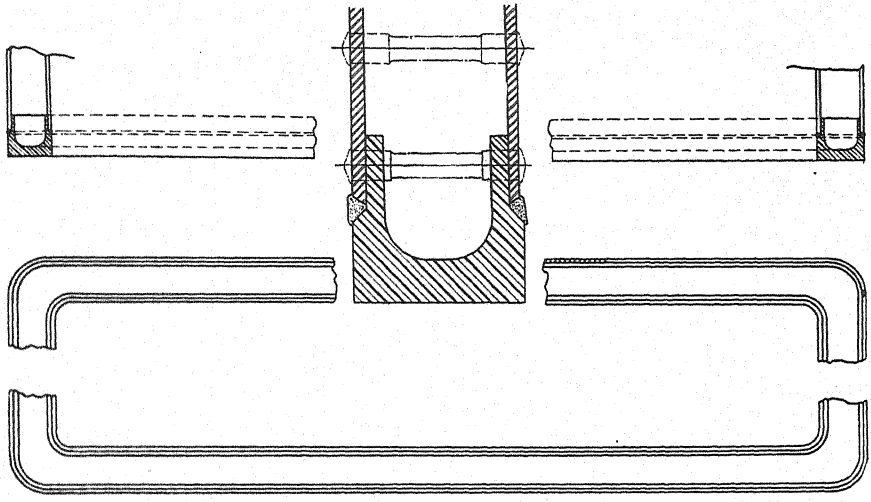


Fig. 34—Firebox Ring

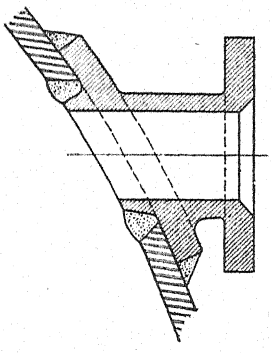


Fig. 35—Injector Check Flange

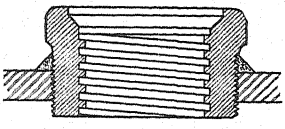


Fig. 36—Washout Plug Bushing

The firedoor hole is formed in the usual manner by flanging the backhead sheet inward and the firebox door sheet outward, neatly butting these flanged edges and joining them by a single-welded butt weld.

The cast steel firebox ring is of a special cross-section with flanges on the top side permitting the attachment of the ring to the firebox sheets by the bottom row of staybolts which are provided with telltale holes their entire length; the welds between the sheets and the ring are for tightness only,

the ring being supported by other means. This construction is shown in Fig. 34.

The injector check flanges, Fig. 35, all washout plug bushings, Fig. 36, all flexible staybolt sleeves, angle attachments for dry pipe support and all bosses that are tapped for other attachments to the boiler were welded to the shell by fillet welds. The bosses were applied for the reception of studs in order to avoid the presence of stud holes in the shell course.

All of the welds in the firebox are double-welded butt welds located between lines of staybolts and therefore not stress-relieved.

All of the welds in the boiler shell were stress-relieved in accordance with the A.S.M.E. Boiler Code requirements for power boilers.

In stress-relieving the boiler shell the furnace temperature was brought up slowly to 1150°F., held at that temperature for $2^1/_4$ hr. and then allowed to cool slowly.

Before the boiler shell was placed in the furnace, the firebox ring was bolted in place as a stiffening member and the flat and circular parts of the shell were thoroughly braced to prevent distortion. The stress relieving was accomplished without any change in contour.

The bracing and firebox were then installed, staybolts and tubes applied and the boiler completed without any reshaping being required.

The bracing and staying of the backhead and front tube sheet are of the usual type for locomotive boilers. The bracing tees are riveted to the flat portions of the heads, the crow feet are riveted to the shell and the brace rods are of the weldless type with pin connections.

The tubes are applied in the normal manner and seal welded for tightness at the firebox end.

The boiler was given a hydrostatic test at twice the working pressure after the welds had been hammer tested under a hydrostatic pressure of $1^1/_2$ times the working pressure.

The boiler was then used in stationary service, without lagging or jacket, and following six weeks of such use the locomotive was placed in road freight service on September 24, 1937.

In conformance with the rules submitted by the railroad for subsequent handling the jacket and lagging were removed and all welded shell joints examined each three months in the first twelve months of service, and each six months in the second twelve months of service. In the third year a similar examination was made after the expiration of twelve months service and this will be repeated after each twelve months' service until the expiration of the five-year test period. Hydrostatic tests at 50% in excess of the working pressure were applied after each twelve months service. At these examinations all welding was found in good condition.

To December 31, 1940, the locomotive has made approximately 190,000 miles in road service since installation of the welded boiler and the expectancy of the project has to date been fully realized.

Locomotive Tenders

Tender Tanks.—Tanks are being fabricated by the fusion welding process in an ever increasing quantity and satisfactory methods have been gradu-

ally developed. The plate material is usually tank steel; various types of corrosion-resisting steels are also used.

Tees or angles employed as stiffeners for the relatively thin sheets, and to attach swash plates, are generally welded with intermittent fillet welds although in some constructions continuous welds have been used. The locations and arrangement of the tee or angle stiffeners have not been standardized and vary considerably with different designs. In some designs the cisterns are all welded and the swash plates are attached to the tee or angle stiffeners by riveting, in other instances all attachments are welded. The welds in the outside sheets are continuous single-welded butt welds to present a smooth surface.

Welded swash plates, braces and bulkheads are generally fabricated ready for attachment by welding in their proper positions in the tank to permit the major portion of the welding to be done in the open, thus leaving very little to be performed inside the tank after it becomes a partially closed structure.

These tanks are generally of the rectangular type though a number of semi-Vanderbilt flat-top tanks have been completely fabricated by fusion welding. When constructed for use with oil burning locomotives some of the tanks have two separate compartments—one for water and one for fuel, while others have separate fuel oil tanks that fit into the conventional coal space.

Welded tanks have been constructed with plate bottoms for mounting on the so-called "open bottom" type tender frames which have floor boards upon which the tank rests. Others are built on cast steel water bottom tender frames which form the bottom of the tank and to which the tank plates are welded.

Repairs to welded tender tanks follow the same methods as used in original construction. Cracks in the sheets are welded if the condition of the base metal warrants, sheets and part sheets are renewed, cracked swash plate and bracing welds are rewelded, and reinforcing in the form of tees, angles or plates is applied to parts and in locations that show evidence of distress.

Tender Frames and Tender Truck Frames.—A limited number of tender frames are made of structural steel shapes, H-beams, I-beams or channels with the necessary cross-bracing transoms, end bumpers, etc., which are fusion welded almost entirely with fillet welds.

Whenever possible this work is stress-relieved but good service results are being obtained from assemblies which are not stress-relieved. In this work for best results it is important that the welding be done in a down position.

In common with welded tender frames the number of tender truck frames that have been constructed by fusion welding is limited. The welds are usually of the fillet type and the same procedure as that employed for tender frames has been found to give the best results. Some of these trucks are made of structural material with steel castings for the more complicated portions, partially welded and partially riveted.

Repairs to welded tender frames and welded tender truck frames follow the same procedure as for new construction.

One-piece cast steel tender frames, many of which are of the water bottom type, one-piece cast steel tender truck frames and cast steel truck side frames are very generally used by all railroads, and repairs to these members can best be effected by fusion welding. The procedure followed in applying repairs to cast steel tender frames and cast steel tender truck frames is similar to that for strength welding of steel castings of comparable section and repairs to cast steel truck side frames are made in conformance with rule 23 of the Association of American Railroads Code of Interchange Rules governing the condition of and repairs to freight and passenger cars.

RAILWAY TRACK WELDING

Fusion welding has in the past few years come to take an important place in railway maintenance of way work and has effected great economies by enabling railway joints, angle bars, rail ends and other details to be kept in good operative condition. This section undertakes to outline the development of fusion welding repair work on railway track joints, frogs, crossings and other special track work. The section is intended to be general in scope and its terms are broad enough to cover all processes of fusion welding except as specially noted herein.

Building Up Rail Ends

One of the most widely applied welding repair practices is the building up of worn rail ends. The life of rail in track can be greatly lengthened and the riding condition of the road bed greatly improved by restoring the worn condition of rail ends which results from wheel batter. An outline of the rail end welding procedure of the Chicago, Burlington & Quincy Railroad is presented as an example of one that has given satisfactory results over a period of many years of usage.

Before proceeding with the welding of battered rail ends it is desirable to tighten the angle bar bolts and check the fit between the angle bars and the rail with thickness gage. Replacement of the angle bars is necessary before starting the welding operation if:

(*a*) The 0.006-in. gage can be inserted between rail and bar fit.
(*b*) Bar is drawn in against web of rail at fishing surfaces.
(*c*) Bar is checked or cracked.

There are certain conditions which will render the joint unsatisfactory for the application of the welding, and these conditions can be corrected as follows:

(*a*) By replacing worn bars with new or reconditioned angle bars.
(*b*) By reversing angle bars when one end of bar is only slightly drawn in at fishing surfaces; the other end of bar being drawn in against the web, but loose under the ball of rail.
(*c*) By the use of angle bar shims.
(*d*) By flame straightening angle bars.

In determining what rail ends should be welded there are a number of economic factors that should be given consideration as follows:

(*a*) The general condition of the rail.

(*b*) The amount and speed of the traffic over the rail.
(*c*) Probable life in the location in question.
(*d*) Possibility of use in secondary lines.

The most satisfactory and economic results will be obtained by welding out of face when 50% of the joints in any stretch are battered or mismatched by 0.030 in. or over, or by spot welding where a small percentage of the rail is badly chipped, battered or mismatched, the latter condition being brought about by changing failed or broken rail. In determining the minimum and maximum limits of batter of rail ends that should be welded, the following considerations should govern:

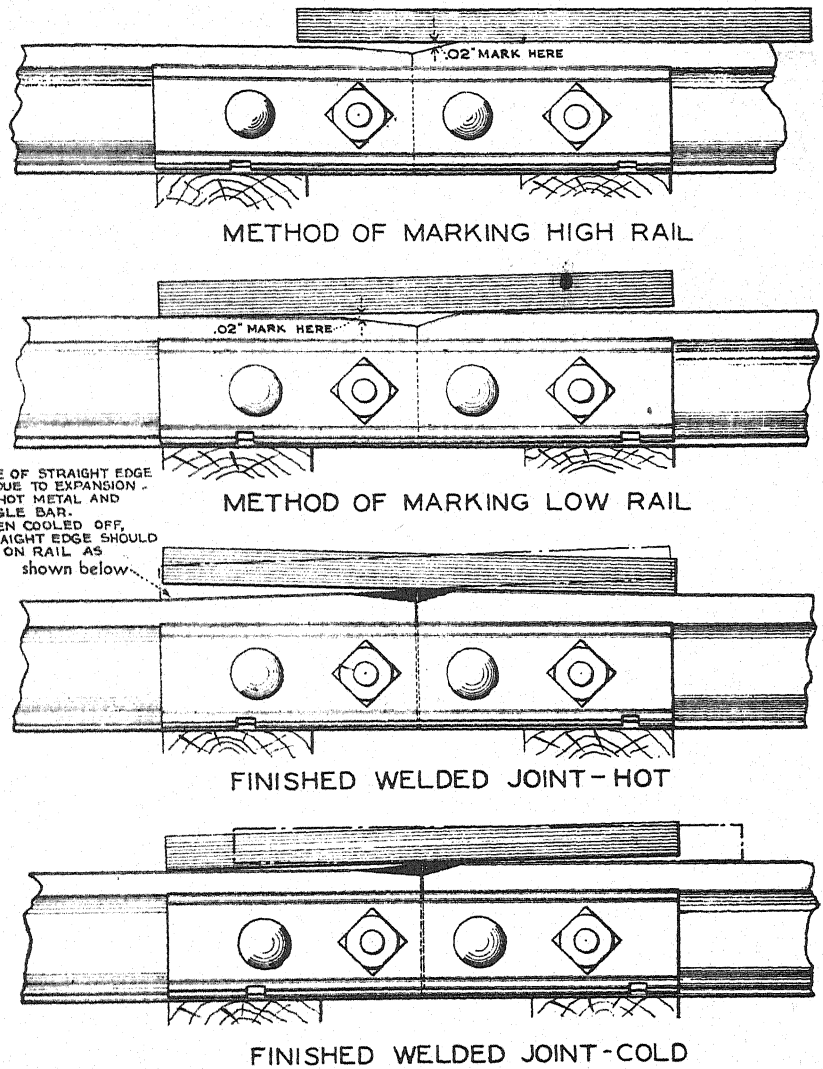
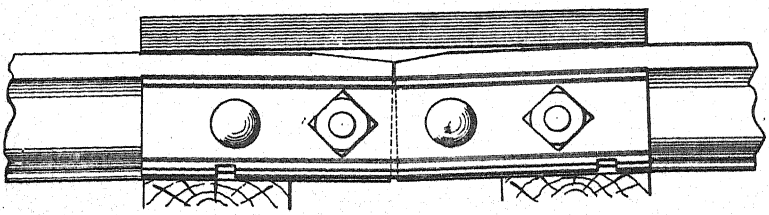
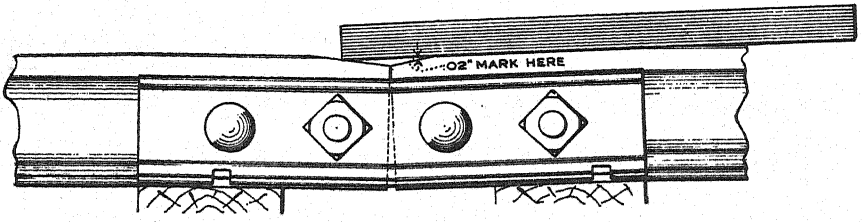


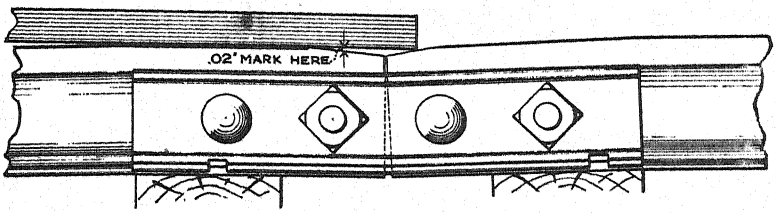
Fig. 37—Building Up Rail Ends



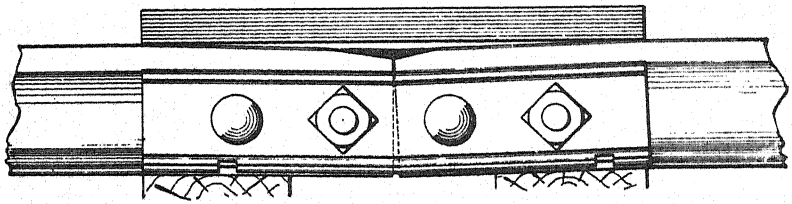
LOW OR BENT JOINT



METHOD OF MARKING R.H. RAIL



METHOD OF MARKING L.H. RAIL



FINISHED WELDED JOINT - COLD

Fig. 38—Repairing and Building Up Rail Ends

(*a*) No minimum depth recommended for high-speed main tracks.

(b) Weld all joints of 0.030 in. or more on secondary lines or on freight traffic lines operated at slow speeds.

(*c*) No limit to depth of weld, but no welding permitted on rail beyond last bolt hole in angle bar.

The procedure to follow in marking joints to be welded is shown in Figs. 37 to 40. It is desirable to use a 24-in. straight edge together with a taper gage to determine the depth and the length of the weld that will be necessary. A chalk mark should be placed on each rail in order to indicate

the length of weld that should be applied. When it is the purpose to finish the joint with a flatter the straight edge should be so manipulated as to eliminate measuring bend in angle bar or low joint. A mark should be placed at the point where the taper gage can be inserted between the straight edge and the rail up to a thickness of 0.020 in. If the welding is to be finished by grinding, the straight edge should be placed on the rail with the center of the straight edge at the joint and a mark placed on the rail where the thin edge of the taper gage can be inserted.

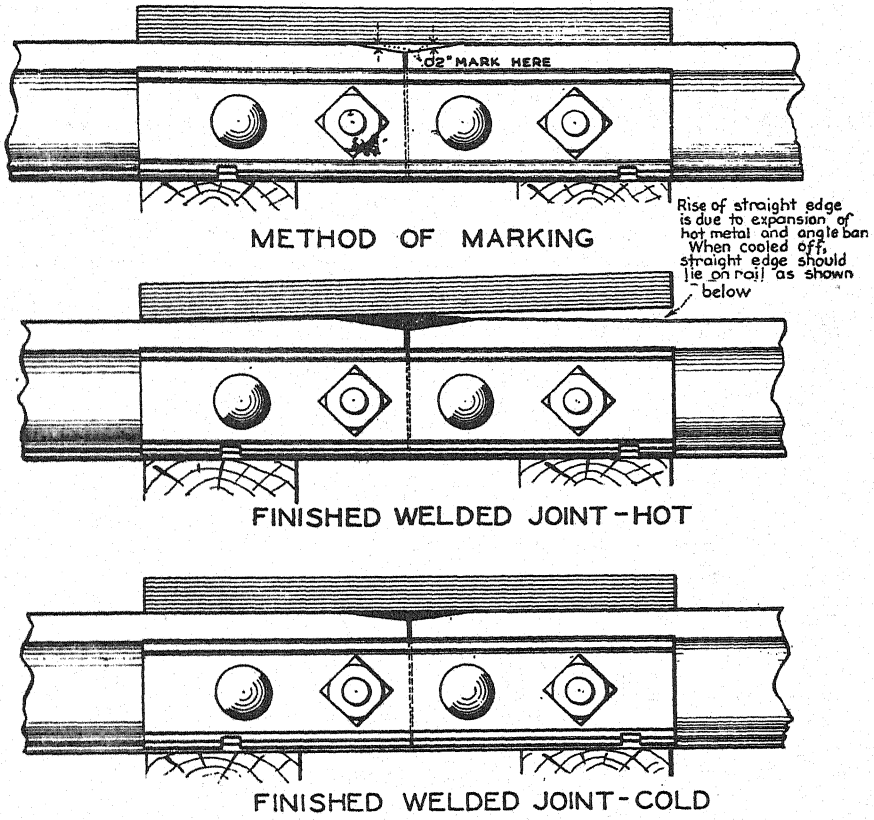


Fig. 39—Finishing Weld, Closed Joints

For the purpose of finishing the joints after building up the rail ends by welding, the blacksmith flatter and hotcut chisel may be used when:

(*a*) Rail batter is short (extending only slightly beyond first bolt hole in rail).
(*b*) There is sufficient work to maintain permanent organization.
(*c*) Spot welding is being done.
(*d*) Welding at locations where view is obscure (unless traffic is stopped).

On the other hand the grinder method of finishing the joints should be

used when long welds are necessary, or there is not enough work to maintain a permanent organization.

Where oxyacetylene welding is to be used for building up the rail ends, it is desirable that a carefully established welding procedure should be followed. The size of welding tip is important and it is recommended that a tip be selected which consumes from 60 to 70 cu. ft. of oxygen per hour. The most satisfactory results will be obtained by using a soft flame.

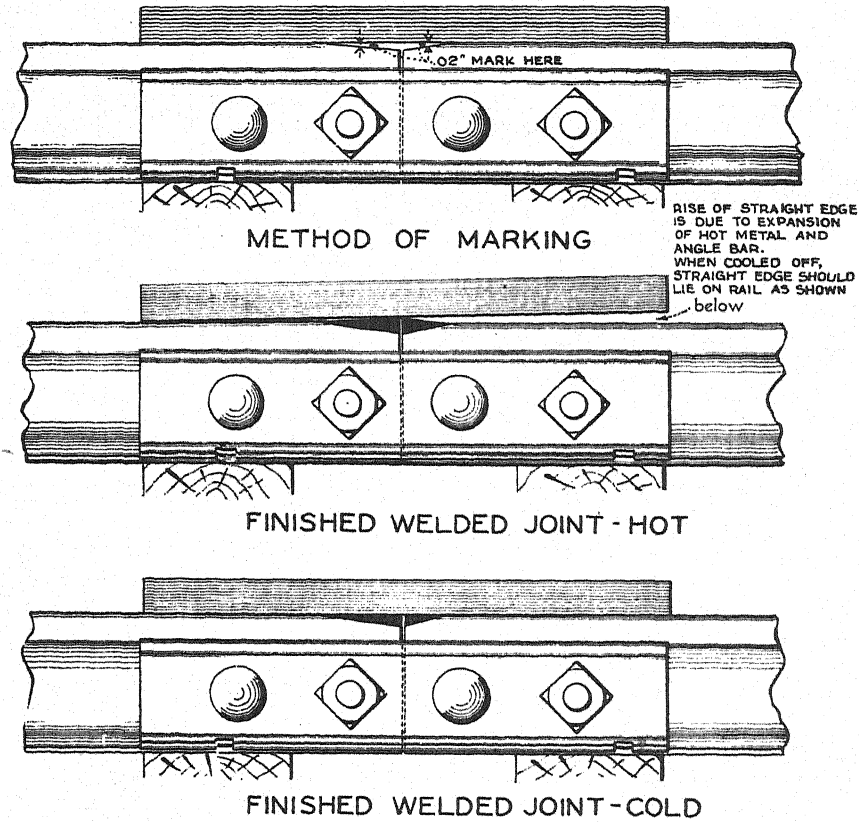


Fig. 40—Finishing Weld, Open Joints

The welding torch should be adjusted for a neutral flame for (*a*) heating when getting ready to apply the metal; (*b*) melting out loose or laminated metal or (*c*) reheating to smooth with flatter or make cut with hotcut. The torch should be adjusted for a slight excess of acetylene flame for (*a*) application of the weld metal to insure against an oxidizing flame, or (*b*) for fusing in and smoothing out the weld metal. For the oxygen and acetylene pressure adjustments, the pressures recommended by the equipment manufacturers should be used. The proper adjustment of pressures must be made at the regulator to insure correct performance of the welding flame.

In connection with the application of welding work as above outlined, it is important that the following items of management be adhered to:

Welding Operations

(*a*) No welding is permitted on the rail outside the limits of the angle bar.

(*b*) Horizontal split head rail can be satisfactorily welded if such split head is at end of rail, and there are no other such failures in the remaining portion of the rail.

(*c*) In welding horizontal split head rail, remove the section by the use of a track chisel and sledge hammer, driving the chisel in where the pieces have separated.

(*d*) It is permissible to heat up a rail for bending if the torch flame is not allowed to come in direct contact with the railhead, and the torch is oscillated over the surface being heated so that the surface of the rail is not melted.

In the actual application of the weld metal to the rail ends the following procedure should be observed:

(*a*) Apply the metal by puddling into parent metal.

(*b*) Apply metal in patches of such size that it will not be necessary to reheat for hammering and smoothing with flatter. Build parallel deposits and avoid applying any weld metal near the sides of the rail.

(*c*) Do not heat up the entire surface of the rail end before starting to apply the metal; heat up only enough to extend a little beyond the patch of metal that is to be applied.

(*d*) Apply metal to or from the 0.020-in. marks, feathering off the rail surface beyond the marks.

There are some differences in procedure necessary when welding open joints as compared with the welding of closed joints, and insulated joints require a very special procedure. When the joints are open the following procedure is desirable:

(*a*) Where there is approximately $^1/_4$ in. between the rail ends, finish each rail end separately.

(*b*) Start application of weld metal on rail end with short batter, and build rail end up to straight edge; smooth with hand hammer.

(*c*) Use flatter to smooth welded surface after each patch if more than one patch is necessary; work flatter from thin end of weld toward the end of rail.

(*d*) Use $2^3/_8$-in. hotcut chisel to make straight cut at end of rail; then put bevel on top end of rail approximately $^1/_8$ in. back from end of rail about $^1/_8$ in. deep.

(*e*) Care must be exercised in cutting these $^1/_4$-in. joints that the chisel does not strike the top of angle bar.

In case the joints are closed the welding procedure should be as follows:

(*a*) When there is less than $^1/_4$ in. between the ends of the rail, make cut with hotcut chisel before application of weld metal is begun.

(*b*) Start applying metal on rail end with short batter, and build up to the proper height.

(*c*) Smooth with hand hammer.

(*d*) Drive hotcut chisel in between the ends of the rails.

(*e*) Smooth the welded surface with the blacksmith flatter.

(*f*) Use $1^3/_4$-in. hotcut chisel to cut bevel on top surface of end of rail; bevel approximately $^1/_8$ in. back of rail and approximately same depth.

(*g*) Apply metal on unfinished end at joint, starting at the end of the rail and working toward thin end of batter.

(*h*) After each patch, if more than one necessary, smooth with flatter; finish end of rail same as above described.

In the case of insulated joints the welding procedure should be supplemented by the following considerations:

(*a*) Weld in the manner described for "open joints" after the insulating materials have been removed, and a pair of straight angle bars have been applied.

(*b*) Care must be exercised that there will be no sharp edges left at end of rail; such edges will cut away the insulation.

(*c*) Only one insulated joint should be welded at a location at any time; the other joint being welded after insulation has been replaced in the welded joint.

Welding Open-Hearth Frogs

The economic factors to be considered when determining whether a frog should be welded or not, are: (*a*) the general condition of the frog, (*b*) the kind, amount and speed of traffic over it, (*c*) the accessibility of location to a welding unit and (*d*) the probable life of the frog at the location in question. The most economical and satisfactory results are obtained by (*a*) welding frogs before the batter (dropped from point rail to wing rail) exceeds $^{5}/_{8}$-in., (*b*) welding frogs with slight batter, if not previously welded, when they are being welded at locations not easily reached by the welding unit or (*c*) welding the frog before it has become so badly battered that filler blocks will not hold wing rails and point rails in proper relative positions; before frog point bolt holes have become elongated and before frogs are badly surface bent. In order to measure the batter on a frog the following items should be taken into consideration:

(*a*) Relative height of point section and wing rail section back of the point of wheel transfer frog point to wing rail.

(*b*) Condition of the filler blocks and bolts.

(*c*) Relative wear on individual wing rails.

Measurement should be taken between the thin end of the frog point and the section where the point section and the wing rail section are approximately the same width as shown by the wear of the wing rail section of the wheel treads. Measurements should be taken by placing straight edge across the frog, one wing rail to the other, and taking distance between the straight edge and inside edge of wing rail. Consideration must then be given to the condition mentioned in items *a*, *b* and *c* above.

The procedure to be followed in marking frogs for welding is shown in Fig. 41.

(*a*) Place the straight edge across the wing rails at the heel end of the frog and note the relative heights.

(*b*) If the point section is $^{3}/_{16}$ in. or less below the wing rails, lay straight edge lengthwise of point, hold it down on heel end of frog and mark the point where the straight edge and surface of frog point separate.

(*c*) If the point section is more than $^{3}/_{16}$ in. below surface of wing rails, place straight edge across frog, one wing to the other, at the point of wheel transfer from frog point to wing rails, determine depth of weld necessary to bring frog point up to within $^{3}/_{16}$ in. of wing rail surface; then place mark at heel end of frog point at such locations as will make a good runoff.

(*d*) Place straight edge on center of wing rail with one end of straight edge even with thin end of frog point; the other end extending toward toe of frog;

hold straight edge down on rail at the toe end of frog, and place a mark on rail where straight edge and wing rail surface separate.

Where oxyacetylene welding is to be used for frog points it is desirable that a carefully established welding procedure should be followed, generally

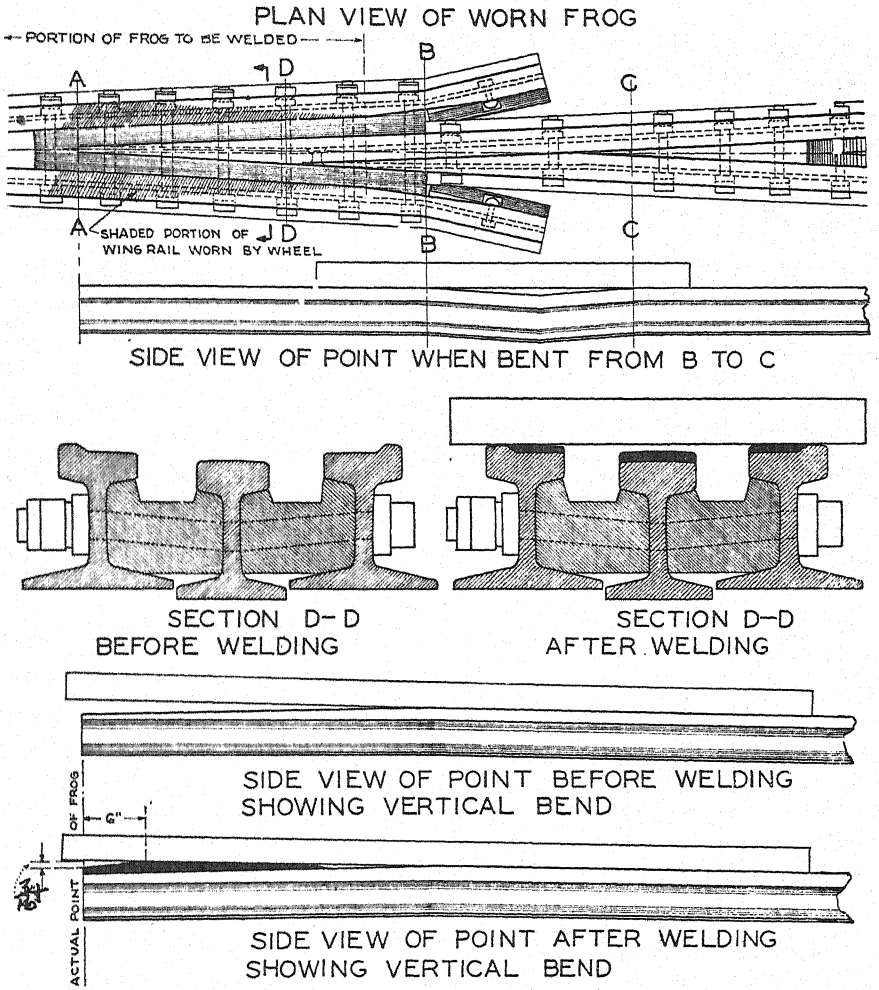


Fig. 41—Welding Worn Frog Points

very similar to that followed for building up rail ends. The size of welding tip should be one that consumes from 60 to 70 cu. ft. of both oxygen and acetylene per hour. For the thin end of the frog point a tip should be used for consumption between 50 and 60 cu. ft. of oxygen and acetylene per hour. The most satisfactory results are obtained by using a soft flame. The torch adjustments for the welding flame to be used should be the same as those outlined for rail end welding.

The comments under the heading of welding rail ends, on proper organization of the welding gang, apply with equal force to frog welding operations. It is desirable in general to work one welding operator and one helper as a unit. One unit should be assigned to a sufficiently large territory so that the welding operator and his helper can be employed permanently. This territory should not be so large, however, that any frog cannot be welded promptly when necessary.

In general it can be stated that a frog is not in satisfactory condition for welding if (*a*) the bolts are loose, (*b*) the frog is badly surface bent, (*c*) it is not properly supported by ties, (*d*) the guard rail is out of adjustment, allowing side wear on the point or (*e*) the angle bars on the joints at the ends of the frog are loose. The above unsatisfactory conditions may be corrected as follows:

(*a*) Tightening and replacing necessary bolts.

(*b*) Placing plates of proper thickness under center of frog before welding; jacking up and blocking frog under bend and applying considerable heat to both wing rails.

(*c*) Replacing ties or shimming up temporarily with steel or wood shims.

(*d*) Setting guard rail properly, or spiking frog in proper gage.

(*e*) Replacement of angle bars or tightening bolts on bars at end of frogs.

When the frog is ready for the weld metal to be applied the recommendations appearing under the heading of rail end welding are here applicable with equal force. Overhanging metal on the sides of the point and on the inside edges of the wing rails should be removed with a hotcut chisel after the application of the weld metal, unless the condition of the parent metal makes it necessary to melt away the overhang before the welding is begun.

In the application of the weld metal to rails the following precautions should be observed:

(*a*) Use a small flame to apply metal and puddle it into parent metal, keeping welding rod in center of pool.

(*b*) Apply metal in patches about 3 to 4 in. long.

(*c*) Start work on heel end of frog at the first point of wheel transfer, frog point to wing rails, by applying the first bead on inside edge of wing rails.

(*d*) Proceed with bead toward toe end of frog for length of patch to be applied; then work back to starting point allowing metal to overhang on inside edge of wing rail; continue in this manner until sufficient metal has been applied.

(*e*) Hammer smooth with hand hammer starting at outside edge of weld metal, working toward inside edge.

(*f*) On inside edge of wing rail, swing hammer as near to the horizontal as possible, starting at lowest point on wing rail and working toward top surface to round off corner.

(*g*) Use hotcut chisel to remove overhanging metal even with inside edge of wing rail.

(*h*) Use flatter to smooth, starting on inside edge; turn flatter slowly from horizontal to vertical, rounding off the top inside edge of rail; then continue toward outside edge of weld section.

(*i*) Apply all metal in patches in the manner just described until wing rail is completed.

(*j*) Make each layer of every patch slightly shorter than the previous layer so that the end of patches will not be perpendicular.

(*k*) The weld from first point of wheel transfer to the approximate end of frog point should be level with the unworn section of the wing rail back of the first point of wheel transfer from frog point to wing rail.

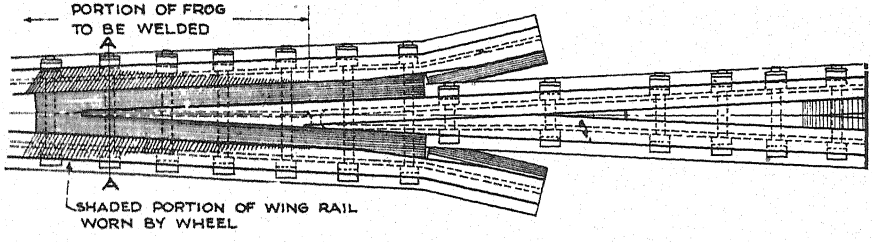
(*l*) From thin end of frog point to mark on toe end of frog, weld metal will be reduced in height as each patch is applied.

(*m*) Build up the opposite wing rail by following the above methods.

When the weld metal is to be applied to frog points, however, the precautions should be considered on the basis of the following items:

(*a*) Start applying metal at heel end of frog point, working toward the thin end.

(*b*) When frog point is more than $^3/_{16}$ in. lower than wing rails, build the frog point up so that it will be not more than $^3/_{16}$ in. below surface of the wing rails. Then make proper runoff in direction toward heel of frog, keeping frog point level from the former place to the thin end.



PLAN VIEW OF WORN FROG

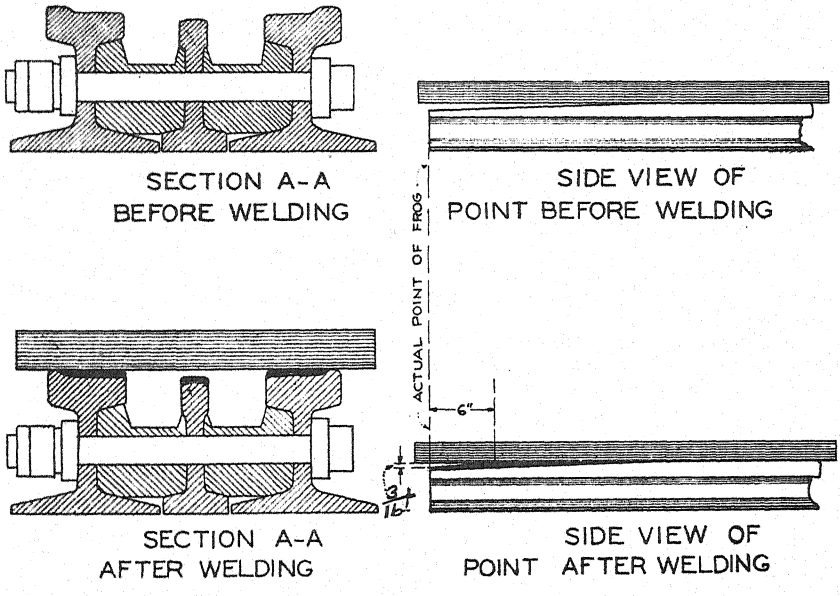


Fig. 42—Welding Worn Frog Points

(*c*) When frog point is $^3/_{16}$ in. or less below the surface of wing rails, build frog point level from mark placed on rail to thin end of frog point. Thin end of finished frog points should be between $^3/_{16}$ in. and $^1/_4$ in. lower than wing rails.

(*d*) Apply the first layer of weld metal so it will overhang edges of the frog point, following same procedure as described for wing rails.

(*e*) The thin end of frog points should be welded before the frog is allowed to cool, or the frog point section must be reheated back to the section where the weld is to be made.

It is economical to weld frogs in position unless the traffic is so heavy that at least one frog cannot be completed per day. This practice involves the least investment for frog replacement and it is not necessary to weld the rail at the frog ends each time the frog is welded. When welded in position in the track the frog can be welded to suit the location. There are disadvantages, of course, in that the welding costs may be increased because of delay on account of traffic, weather conditions, etc. Also there is the possibility of heavy loads passing over red hot frogs, unless extreme care is taken to allow the metal to cool before the section is loaded.

The welding of frogs at a centralized shop has outstanding advantages because of the better facilities for handling, straightening the parts and replacing bolts. In addition there is less delay in the welding operations and there is a reduction in welding costs effected by the use of generated acetylene. The disadvantages of taking the frogs out of track and bringing them to the shop are the cost of removing and replacing and the increased investment involved in carrying a number of replacement frogs. An attendant disadvantage lies in the necessity of making every frog so that it will be suitable for any location which involves the extra cost of changing the rail at frog ends to match the rail on the frog. Warping can be corrected by applying heat along base of frog rails to counteract heat applied to top surfaces.

There are certain precautions to be followed in the repair by fusion welding of self-guarded frogs. On the wing rails and point sections the procedures outlined above for other frogs should be followed. Both in preparation for welding and in the application of the weld metal the following procedure should be observed.

(*a*) Be sure that guard rails on frog are drawn in to proper position.

(*b*) Measure distance from side of frog point to inside edge of guard rail on opposite side of frog point.

(*c*) Start application of weld metal in heel end of guard rail, working toward toe end of frog; increase width of guard rail as necessary to make distance mentioned in paragraph *b*, above, $4^1/_8$ in.

(*d*) Continue welding toward toe end of frog as necessary to make good runoff.

(*e*) Restoring guard rail to original width is not always sufficient to provide proper protection to the frog point.

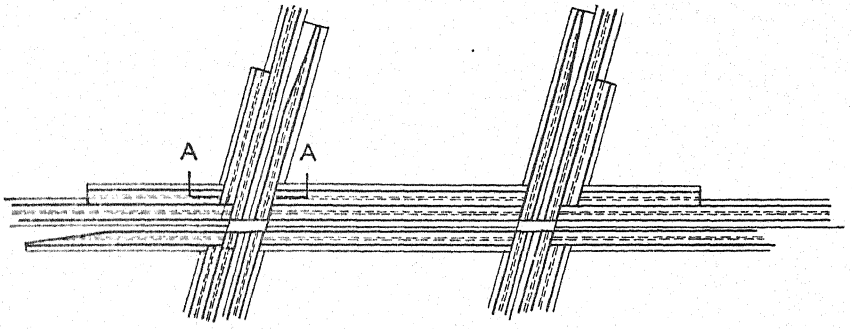
(*f*) Start application of metal on bottom edge of guard rail, and apply in beads sufficiently heavy to allow for trimming.

(*g*) Do not permit traffic to pass over frog, except at very slow speed, while guard rail is being welded; unless runoff is made at end of patch being applied, after metal is allowed to cool.

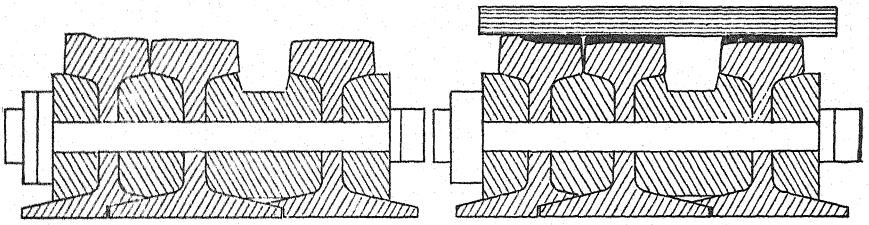
(*h*) A special angle-faced flatter should be furnished to smooth up the inside edges of guard rails.

The repair by fusion welding of railroad crossings, as shown in Fig. 43 calls for certain special considerations. In general the procedure outlined for welding of frogs should be followed but there are additional precautions to observe, as follows:

(*a*) Inspect rail for incipient cracks at junction of web and ball.
1. Replace defective sections in high-speed track.
2. Welding is permissible in slow-speed track, but regular inspection should be made.



PLAN VIEW OF WORN XING



SECTION A-A
BEFORE WELDING

SECTION A-A
AFTER WELDING



SIDEVIEW
BEFORE WELDING

SIDEVIEW
AFTER WELDING

Fig. 43—Welding Railroad Crossings

(*b*) Build up riser rails to match running rails, and keep top surface of such rails separated by beveling with hotcut chisel.

(*c*) On crossings where traffic causes uneven wear:

1. Select the line with heavier traffic and wear.
2. Build up such rail as necessary to make smooth wheel transfer.
3. Build up or reduce lighter traffic line to match rail on the heavier line.

Welding Switch Points

The following suggestions are offered with regard to procedure in welding switch points:

(*a*) Use a tip which consumes about 50 to 60 cu. ft. of each, acetylene and oxygen, per hour.

(*b*) Start application of weld metal on thin end of point.

(*c*) Apply metal in patches following procedure outlined in frog welding.

(*d*) Smooth weld metal with hand hammer, and trim off both sides of point with hotcut chisel; then smooth with flatter.

(*e*) Build up point to match stock rail, keeping thin end of point slightly below top surface of stock rail.

A switch point will be found unsatisfactory for repair by welding if it is badly side worn for the full length of the point and has no definite reduction in width as the thin end is approached. It will also be unsatisfactory for repairing if the stock rail is badly worn, flattened, chipped or if there is a heavy bead on the inside edge of the stock rail which does not permit the point to close. Such unsatisfactory conditions can be corrected by changing the stock rail or reversing it, or, if the rail is in good condition except for the bead by removing the head by grinding or cutting.

The question as to whether switch points should be welded in or out of track depends upon a number of conditions such as the necessity of matching the point up to a stock rail; if the point is welded out of track it cannot be welded up to a selected rail and give satisfactory results. Points welded in track can be straightened by the following methods:

(*a*) Heating base and ball sections, and using track jack, either spiking down end of point or using heavy bar to make bend.

(*b*) Applying heat to base of rail only.

Points welded out of track can be straightened by the following methods:

(*a*) Placing plate under bend and clamping down before welding.

(*b*) Placing in rail straightener after welding operation completed.

In welding points in track care must be exercised to prevent trains from passing over the weld when the metal is hot except at slow speeds, or when proper runoff is not provided.

Butt Welding of Rail

The butt welding of rail ends is desirable and will give economic results for conditions encountered in street crossings in city streets, in tracks along depot platforms, on bridges, in tunnels, scale tracks, turntable tracks and circle rails. If the rails are butt welded in these locations the batter

ordinarily experienced in bolted joints will be eliminated and the upkeep of the track considerably simplified. Below are given the governing considerations and the recommendations for preparation for end procedure in such welding work.

Several methods may be employed for the butt welding of rail namely: Flash, Thermit Pressure, Oxyacetylene (Hand) and Oxyacetylene (Pressure). These methods are described elsewhere in this chapter.

Manganese Frogs and Crossings

While it is the practice of the Chicago, Burlington & Quincy Railroad to utilize oxyacetylene welding only for the repair of open-hearth frogs and crossings, in the case of manganese frogs and crossings it has been found that electric arc welding is preferable on account of the manganese constituent in the material.

Under this heading, therefore, recommendations will be presented which pertain solely to electric arc welding and they will be tabulated in very much the same order as in the instructions previously given.

The general procedure for inspection, marking, measuring batter and preparing for welding is very much the same as that outlined above for open-hearth steel frogs. It should be pointed out, however, that frogs and crossing sections should not be welded if (*a*) they are badly cracked longitudinally in filler sections, or (*b*) they are badly cracked across wing or point sections when such cracks extend into fillers and cannot be removed so that the weld may be started at the bottom of the crack. In preparing to apply the weld metal the following precautions should be observed:

(*a*) Clean all surfaces upon which metal is to be applied.

(*b*) Remove all loose or laminated metal and all cracks in wing and point sections.

1. Use oxyacetylene cutting torch, cutting away such sections as necessary to remove defective metal and permit grinding on cut surface.
2. All defective metal may be removed by grinding, but the method outlined in paragraph *b*1 is most economical and satisfactory.

The weld metal should be applied in repairing manganese parts under the following conditions:

(*a*) Apply metal in beads running longitudinally with wing and point sections.

(*b*) Peen each bead after application of each electrode.

(*c*) Apply one layer of weld metal over surface to be welded, then apply successive layers as may be necessary to restore section to proper height, allowing for finishing by grinding.

(*d*) In building up sections where necessary to cut or grind away a large section to remove defective parent metal,

1. Apply metal in thin narrow beads.
2. Keep section as cool as possible by intermittent welding.
3. Apply metal so as much contraction as possible takes place before application of bead between parent and weld metal is made at edges where section is removed.

When it becomes necessary to finish the frog or crossing sections after repair by welding, the following procedure is advised under these conditions:

(*a*) Grind top surfaces of point and wing rails smooth, leaving them in proper relative heights (see section on open-hearth frogs).

(*b*) Grind off overflow or overhanging metal on sides of point and inside edges of wing rails, rounding off top edges.

(*c*) Leave thin end of point section approximately $^{3}/_{16}$ in. below surface of wing rails.

(*d*) On solid manganese crossings, grind top surface of wing rails at section near open-hearth rail fit.

Satisfactory repairs can be made in welding cracks in the base of sections by using nickel-manganese applicator bars. For this the surfaces of the section should be cleaned on both sides of the crack. The applicator bar should be cut to proper length and laid across the crack and then welded to the cracked section.

For the welding of the manganese sections the most satisfactory and economical results will be obtained by using a manganese welding electrode having a nickel content. The welding gang should consist of a foreman, a welding operator and a helper in the regular crew. A man should be furnished locally to assist when the welding is of such a character that both welding and grinding can be done simultaneously, or when working at locations where the welding work is being done in the track and the view is obscure.

The equipment necessary for carrying the above welding work along is as follows: (*a*) a complete set of oxyacetylene welding and cutting equipment; (*b*) 300-amp. 35-volt gasoline driven arc-welding set, preferably designed for movement on rails; (*c*) gasoline-driven surface grinder equipped with flexible shaft take-off attachment and (*d*) electric-driven portable grinder.

Hard Surfacing

Hard surfacing finds numerous applications in railway maintenance work. By it the efficiency is increased and considerable life is added to car retarder parts such as lugs on driving bars, hold-down bars, yoke bearing plates, driving links, holes in driving bars and other reciprocating parts. The hard surfacing material is merely applied by fusion welding to both surfaces where wear occurs and any high spots therein are removed by grinding.

Switch slide plates constitute another economical application of hard surfacing. This application increases the operating efficiency of signal interlocking plants and is also beneficial when applied in other locations having power throw switches, especially where the traffic is heavy. It has recently been discovered that where hard surfacing is applied to switch slide plates the adhesion of ice is lessened.

Another extensive use of hard surfacing is on drag line excavators, on ditches and clamshell buckets, lips and teeth and on the edges of Jordan spreader plows. These parts may be built up by fusion welding using

nickel-manganese alloy steel, although hard surfacing is a very economical application for most of these parts. Where subject to excessive wear due to hard or sharp ballast material, tamping tools may be hard surfaced with great economy. When these wearing surfaces are hard surfaced it is found that the tools will outlast similar tools with plain steel ends and edges from 5 to 10 times, and in addition, they are more efficient in use.

Rail End Hardening

An application of the oxyacetylene process which has proved very effective in track work is the hardening of rail ends which can be done with great effectiveness and economy if new rail has been in service long enough so that the angle bars are "set." For this it is desirable to apply the flame-hardening process so as to increase the hardness of the face of the rail end by approximately 100 points Brinnell; it is not recommended that the hardness be raised above about 400 Brinnell. The hardened area should cross the rail face diagonally, starting about 1 in. from the end of the rail on the outside end and about 2 in. from the end of the rail on the gage side.

In applying the flame-hardening process it is necessary that the angle bar bolts at the joint are tight. The ends of the rail face must be surface ground to match across the joint and all scale must be removed.

It is also necessary to cross-grind the bevel on the ends of the rail. The heat treatment can then be applied to bring the top surface of the rail ends in the desired pattern quickly up to a temperature of 1650°F. This process requires the following equipment: (*a*) the heat-treating unit, (*b*) a surface grinder, (*c*) a cross-grinder and (*d*) a push car for handling the oxygen and acetylene cylinders.

Flame Cutting

It may here be observed that economical and satisfactory results can be obtained from the use of flame cutting for removal of bolts in connection with rail release, the removal of tracks, etc. It is, of course, important that in cutting out bolts, rivets, etc., near a rail, that great care must be exercised that the flame shall not be brought into contact with the rail or the rail nicked by the flame. The cutting torch should be so directed that the angle bar bolt holes will not be nicked.

Most of the cutting in this service can be satisfactorily performed with a No. 2 cutting tip. If the bolts are badly rusted, however, a No. 3 cutting tip can be used to advantage.

The ends of bridge guard rails or rails used for the service of highway crossings may be sloped by flame cutting by either of the two following methods: (*a*) the entire rail end may be cut off by cutting the base, ball and web at an angle, or (*b*) a triangular-shaped section of the web of the rail may be cut out at the end and then the projecting ball of the rail heated up and driven down until it touches the base.

It will be of interest to note the table below containing long-time averages of oxygen, acetylene and rod consumptions pertaining to some of the work covered in this chapter:

Oxyacetylene Welding Process

	Rail Ends	Open-Hearth Frogs	Switch Points
Cu. ft. oxygen	8.055	154.24	66.55
Cu. ft. acetylene	9.562	173.33	74.27
Welding rod—lb.	0.0812	3.37	1.652
Number per welder per day	28.50	1.321	2.460
Number per man day*	13.71	0.6607	1.230

* Covers all men in gang to complete procedure, including grinder operators.

Rail Joint Butt Welding

Butt welding, which has been in extensive use in industry for many years, was first applied to rails—the welding of standard lengths from the mill, end to end, into long lengths, by electric traction systems where the tracks were buried in pavement.

Since about 1929 such practice has been followed extensively by the European railroads for steam railroad open track, several lengths of rail being butt welded, end to end, to make rails of 100-ft. lengths to 225-ft. lengths. The extent and progress of butt-welding rails into long lengths confirms the advantages of this practice in Europe.

American steam railroads, with the development of clip track fastenings of various types, discovered the possibilities of butt welding of standard lengths from the mill, end to end, limited in length only by the necessity for insulated joints required by the signal circuits and switches and, since 1933, have been experimenting successfully with such installations.

Extensive study and research has been carried out, relative to the many phases of welding theory and practice in both Europe and the United States of America. Exhaustive tests of butt welds made under many different procedures, in addition to the well-known rail acceptance tests, were made, the welds being subjected, day and night, to severe rolling load fatigue tests, following a similar procedure of the extensive rail investigations by the University of Illinois, and considered the nearest approach to actual service condition in track. To further assure a high-quality weld, extensive experiments were made relative to various methods of stress relieving. This procedure has developed butt welds which stand up under the severe condition of a 65,000-lb. wheel load. The welds supported as a cantilever, Fig. 44, were subjected to six million passes of the above load. They were then mounted as a simple beam, Fig. 45, and given six million additional passes of the 65,000-lb. wheel load without any sign of failure, equivalent to many years of heavy wheel loads in actual service.

The installations of continuous welded rail on American railroads have been successful and the many advantages, of either long or continuous rail using the butt weld for the elimination of joints, are being recognized more and more.

In some installations, the welds have been made alongside of the track. This has the advantage of allowing the welded rail to be installed in place in long enough lengths to eliminate subsequent closure joints. At the same time there are obvious difficulties in that the work must be done fre-

quently, on narrow shoulders, in open cuts, tunnels and bridges, and in such cases it has been found more economical to carry out the welding at central points on strings of flat or flat bottom gondola cars, using from twenty to fifty cars, governed by the lengths desired or the layout of the tracks, as the number of cars is limited to the tangent track available.

It is possible to complete the welding of some eight to twelve strings of rails on one set of cars and then move them to the location where the

Fig. 44

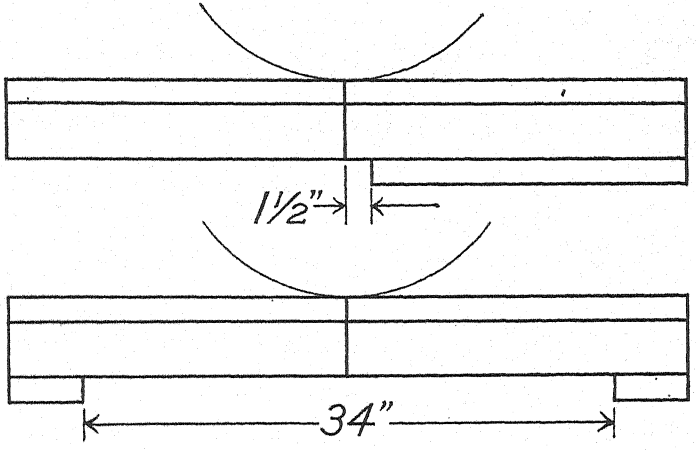


Fig. 45

rail is to be installed, no difficulty being encountered in moving the cars thus loaded around 14° reverse curves.

The unloading of the cars is accomplished by fastening a short cable to the end of continuous rail, the other end of the cable being fastened to the track, the train is then moved slowly forward until only a short length of the continuous rail remains on the cars, the remainder of the rail having come to rest on the track alongside and outside the running rail; the movement of the train is then speeded up to prevent excessive swaying of the last short piece of rail, which has a tendency to cause the rail to turn over. Continuous rail is very flexible and can be readily handled on the ground and, should the ends, where the joint is to be installed, not quite match up, the rail can be moved easily by bucking.

Electric Butt-Flash Welding of Rails

Capacity of Welder.—A welder, suitable for flash-butt welding the rails used most generally today; that is, 112-lb. and 131-lb., should have a transformer capacity of 750 kva. with a secondary voltage up to 14 volts. The push-up pressure should be a maximum of 75 tons.

Preparation and Clamping of Rails.—In preparing rails for flash welding, the ends are cleaned and the scale is removed at the point where the current

clamps engage the rail. Care should be exercised in clamping the rail ends in the welder to insure accurate alignment, as offset or out of line in the welder will tend to introduce undesirable irregularities in an otherwise smooth track.

Welding.—The welding process consists of three phases:

1. Preheating, covering the initial period during which the rail ends are heated by a series of successive flashes accomplished by repeatedly bringing the ends of the rails together and then separating them slightly. This preheating to cover a period of approximately $1^1/_2$ min. for 131-lb. rail. In preheating the rail ends are brought to a temperature which will support continuous arcing or flashing.
2. Flashing is a continuous arcing or burning of the metal, as the rail ends are steadily moved nearer together. In effect, the movement equals the rate of burning of the metal. This flashing period is approximately $^1/_2$ min. for 131-lb. rail.
3. Push-up covers the short interval (approximately 5 sec.) during which the flashing is terminated by butting the rail ends together with a force of approximately 10,000 pounds per square inch. The welding current is switched off immediately following the completion of the push-up. Total loss in rail length due to metal removed by flash and push-up is approximately $1^1/_4$ in. per weld.

Stress Relieving.—During the process of flash welding, stresses are set up in the immediate vicinity of the weld. Stress relieving to correct this condition is accomplished by bringing the weld and the adjacent rail metal in an oil furnace up to a temperature 1200°F. and allowing it to be followed by slow cooling controlled by an insulated hood.

Flash Removal.—The flash or excess metal should be sheared off and ground down below the small notch in the weld to eliminate any notch effect, and the top surface and sides of the head should be finish ground to the exact contour of the adjacent rail.

Thermit Pressure Butt Welding of Rails

The Thermit pressure weld combines a full butt weld of the rail heads with a fusion weld of the webs and bases. The butt weld of the heads is an important feature because, under heavy wheel loads, rail welds in track of standard construction are subject to reverse bending stress, resulting in tension in the welds.

In making the Thermit pressure weld the heating of the heads to welding temperature is brought about by the slag from the Thermit reaction. Rails are carefully aligned and set up for welding with the heads in tight contact and a torch-cut gap $^1/_2$ in. wide in the webs and bases at the joint. After preheating the molds and rail ends, the Thermit, which is a mixture of iron oxide and aluminum, reacts in a refractory-lined crucible to produce quantities of liquid steel and alumina slag. The reaction develops a temperature of nearly 5000°F. Because of the difference in weight, the two materials separate readily. They are tapped from the crucible into molds placed around the rails. The molds are so constructed that the liquid steel flows into the gap in the webs and bases to make a fusion weld of these parts, while the slag floating on top of the steel completely surrounds the rail heads. Pressure with which to effect the butt weld of the heads is

obtained by means of heavy rail clamps, which are drawn up to squeeze the heads together after they have been softened by the heat of the slag.

Oxyacetylene Butt Welding of Rails (Hand Method)

In order to obtain satisfactory results in the butt welding of rail ends the following preparations must be carried out:

(*a*) Rails to be butt welded must be in proper line and surface.

(*b*) If in track provide for at least $^1/_4$-in. expansion between rail ends for cutting operations; otherwise make cut at end of rail before lining and applying angle bars.

(*c*) Cut base, web and ball of both rails forming "V" as small as consistent with depth or width of sections to be welded.

(*d*) Remove all slag and scale with hand hammer and chisel.

(*e*) Apply angle bars; the top section of one bar should be cut away in area between center bolt holes and this bar applied on side of the "V" in web.

(*f*) Drive expansion, leaving $^3/_{16}$ in. between rail ends.

(*g*) Tighten bolts and straight-edge rails to make sure of proper line and surface.

The welding procedure to be followed in applying this butt welding operation is as follows:

(*a*) Heat up the ball of both rail ends, using two torches when available.

(*b*) Start application of weld metal at junction of web and ball, making such application from under side of ball and extending down on web of rail about $^3/_4$ in.

(*c*) Then, start welding in center of ball at bottom of "V," working toward one side and then toward the other.

(*d*) Continue welding on ball, using two torches after weld metal high enough on "V" to permit their use.

(*e*) Keep the weld metal extended well over edge of rail.

(*f*) Use a high-tensile rod about one-half way up "V" on ball of rail.

(*g*) Use rail-end welding rod on ball from approximate center to complete to the top of the ball of rail.

(*h*) Smooth with hand hammer.

(*i*) Remove angle bars.

(*j*) Weld the web from one or both sides starting at bottom of base. (When one welder is used, fuse in and smooth up opposite side of web when weld is completed on the other side.)

(*k*) Weld base, one welder on each side of rail.

(*l*) Apply angle bars and tighten bolts as quickly as possible.

(*m*) Finish top surface of rail by trimming off overhanging weld metal on sides of ball, smooth with hand hammer and flatter.

Where oxyacetylene welding is to be used for this operation the same general provisions for type of welding flame, welding torch adjustments, etc., should be followed as are recommended under the heading Building Up Rail Ends.

The actual size of the welding tip will, of course, be dependent upon the size of the rail and the number of welding operators to be employed. Two welding operators should be used, where possible, using tips which consume 50 to 60 cu. ft. each of oxygen and acetylene per hour. When only one welder is available the above size tip is satisfactory for the base,

web and part of the ball of the rail, but a tip which consumes approximately 70 cu. ft. per hour will be needed to complete the weld on the top of the ball. A No. 2 cutting tip should be used for veeing rail ends.

When the rail ends are to be butt welded out of track the same general preparations and procedure are to be followed as are outlined above for welding the rails in track. When the base weld is completed from the top and angle bars have been applied and tightened, the rail should then be turned on its side and melted out at the line of the weld. Then the necessary metal can be applied to bring the surface back to level.

Oxyacetylene Pressure Rail Welding

The automatic process for pressure butt welding of railroad rails consists of bringing the properly prepared ends of two rails together in a suitable, sturdy machine, clamping them in accurate alignment, compressing the ends together with continuously applied hydraulic pressure, while a series of oxyacetylene welding flames are applied completely around the rail ends at the point of juncture. This heat is applied continuously until the metal of the rails reaches the plastic state. When this point in the welding cycle is reached, the weld is completed. Thus the joining is not a fusion weld but a weld in which the action takes place while the metal is, metallurgically speaking, in the solid state.

A portion of the excess metal at the weld, which has become upset during the welding process, is then removed and the weld zone is reheated to above the critical temperature and allowed to cool in a normalizing operation which refines the grain of the metal.

There have been thorough and extensive laboratory tests of oxyacetylene pressure welded rails and all the results are favorable. In the investigation of continuous welded rail being carried on by the Rail Committee of the American Railway Engineering Association with the cooperation of the Engineering Experiment Station of the University of Illinois, tests show remarkably high qualities. For example, the tensile strength of samples taken from the weld metal average within 2% of the standard of the unwelded rail metal. Ductility, rolling load, bend, drop and nick-break tests were similarly favorable. A test installation installed by this Committee was recently reported to be standing up very well in comparison with several other types of welds being tested in the same track.

Advantages of Continuous Rail

Reduction of joint and track maintenance.
Increased life of rail and ties.
Elimination of rail creepage.
Elimination of necessity of replacing joint bars and reconditioning rail ends.
Elimination of bonding for signal circuits.
Smoother riding.
Reduction of rolling stock maintenance.

Installations of continuous or butt welded rail have been in service on a steam railroad in the United States in open track under similar physical conditions to the jointed rails since 1933 and no adverse results have been

noted. Experience with this type of construction, of which there are now approximately sixty-five track miles in service in open track, in both crushed stone ballast and cinder ballast and miles in tunnels. This indicates that, in addition to the many advantages over jointed track expected of it, there are other important items heretofore not considered, such as, the practical elimination of the side wear of rail on tangent track from nosing, and a great decrease in the roaring or noise, particularly in tunnels.

CHAPTER 40D

AUTOMOTIVE PRODUCTS*

Engine Cylinder Blocks, Oil Pans, Minor Operations on Motor Parts, Exhaust Mufflers, Exhaust Tubing, Fuel Tanks, Propeller Shafts, Front Axles, Rear Axle Housings, Fender Parts Assembly, Chassis Frames, X Members, Automotive Bodies, Large Blanks, Body Assembling, Welding Partly Formed Stampings, Acetylene Welded Seams, Welding Guns, Automotive Wheels, Die Maintenance.

WELDING processes assuring reduced cost of production have only been adopted in the automotive industry after extensive research and exacting inspection. Processes adapted to repetitive operations on a large scale have been developed at great expense to meet exacting requirements and precision equipment.

What may seem to be only a minor change of design of a part may be occasioned by, or the result of, a radical change in welding process or procedure.

It follows therefore that processes applicable one year may be wholly out of step with production requirements in the succeeding one. Processes of welding offering improved results or favorable costs are regularly considered and adopted preferably during periods of inventory, model change, or retooling programs.

Because of the large financial risks involved, changes of design are made only after exhaustive tests in the laboratory or proving ground, and finally adopted only after every phase of production cost, equipment cost, reliability and performance are carefully canvassed for predictable results.

In spite of all precautionary measures it is not unusual that new processes and newly developed machines fall far below calculated capacity, seriously endanger production schedules, new car deliveries, or meet the minimum production requirements only at very high expense in production repairs. Naturally production schedules are planned to take such contingencies into account, but regardless of cost, hand-made parts formed, forged or joined by other processes of welding are sometimes

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used to supplement the production of an expensive machine designed for a single purpose application. It is probable that the successful outcome of more than one process has been due in part to rigid adherence to a production schedule which would not admit of a change of design or process, once the manufacturer was committed to a production schedule.

Information on machines and process performance is freely exchanged between manufacturers, probably to a greater extent than prevails in any other industry. It is therefore probable that important operations are being carried out in nearly all cases in accordance with methods amply justified by careful observation and exhaustive cost analysis.

Engine Cylinder Blocks

A completely machined cylinder block represents a considerable investment in labor and material. Although bases for large Diesel engines have been made up of welded structures, no commercially successful cylinder block of mainly welded construction has as yet appeared in automotive vehicles in this country, even though the water jackets of the individual cylinders of the Liberty motor in 1918 were welded to an outer projecting flange of the cylinder wall. Most welding operations applied to the present universally used cast-iron block are in the nature of production repairs and are not of great commercial importance.

Shrinkage cracks in flanges and thin sections can be repaired under favorable conditions with the electric arc. Some surfaces to be machined can be repaired with the oxyacetylene torch with preheating. Bosses and outer corners that fail to fill due to sand falling in the mold are frequently repaired with the oxyacetylene torch without preheating. In the case of only small repair welds and certainly if the areas are large it is desirable to anneal the block after welding to remove residual stresses which may later cause cracking.

Repairs performed by welding in the valve seats and bore areas to fill scattered gas pockets which become evident with machining are questionable investments because of excessive tool breakage and probable rejection at the end of the production line. Cracks in the bore walls through to the water jacket which show up in the water pressure test usually applied both at the foundry and at the machine shop are generally considered beyond repair.

Defects in cylinder blocks showing up with the frequent inspections between machining operations required by most manufacturers are carefully classified. Those which certainly can be corrected by welding later are allowed to go through subsequent operations before welding repair. Blocks which present any question are preferably shunted to a salvage room for handling by a man specially trained to apply the appropriate welding process. It is desirable to fix the responsibility for such repairs in as small a group as possible, because critical judgment should be exercised that the labor on such repairs may not be greater than can be justified by the salvage cost.

Blow-holes in the bore, if not through the water jacket and not too large, may be cleaned with a special drill and filled with about $^1/_8$-in. diameter nickel wire applied with an a.c. arc-welding tool at about 12 v. The

voltage is not high enough to maintain a steady arc or generate heat of high value, but the nickel wire spatters into the hole enough to be later peened down solidly into place. Excess metal must be scraped away, after which the bore can be honed in the usual manner. It is preferable to perform the repair after the final reaming operation to avoid excessive wear on reamers. Diamond boring after such a repair operation might present some difficulty unless exceptional care is taken to remove excess metal.

Oil Pans

Oil pans in later models are usually made of terne plate, steel with a bright metal coating applied in the rolling process. Welding operations are confined to spot or projection welding of reinforcing strips, and other parts such as baffle plates or deflectors. Drain hole bosses generally adapted to accommodate a threaded plug are usually tin dipped and assembled to the oil pan body with rivets and later soldered at the edge to assure oil tightness or projection welded. The latter precaution is obviously necessary and much facilitated by the tin dip which would make spot or projection welding difficult.

Minor Operations on Motor Parts

Long oil passages in connecting rods partly formed in forging, Fig. 1, partly closed in a punch press operation, with the seam closed with the

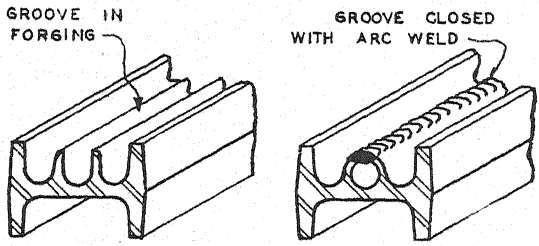


Fig. 1—Oil Passage in Connecting Rod

automatic electric arc, and finally completed from upper to lower bearing bore with a drilling operation were used a few years ago by one manufacturer. Building up threaded ends or portions machined under size on steel parts rejected as unfit for use and recutting is widely practiced.

Applied to heat-treated parts, it is advisable that repair metal should be laid very slowly, preferably with the arc, to avoid drawing the temper of adjacent finish ground surfaces or otherwise damaging the surfaces with spattering metal. Crankshaft counterweights have been welded to the crankshaft body or attached with screws with an arc deposit to retain the screw heads against loosening. Fan belt pulleys at both crank and fan end have been made from stampings in a variety of ways with welding operations in assembly. Generator mountings, breather pipe covers, oil gage parts, oil screen and pump intake parts and many small acces-

sories have from time to time been assembled with welding operations obviously applicable.

It is very important that welding operations on parts inside the crank case or exposed to lubricant should be performed with absolutely the minimum of welding flux and that the surfaces of the completed weld be cleaned thoroughly with the scratch brush or other means. Scaly particles of flux fused with metallic oxides are likely to form abrasives capable of serious damage to bearing surfaces. It is desirable by all means to choose the process and materials least likely to cause such trouble.

Exhaust Mufflers

Exhaust mufflers vary much in type. All models of wide use are made up of stamped or rolled sheet metal parts and only the types of welding readily applicable to sheet metal are employed. The side seams of the outer shell are generally electric seam welded to insure gas-tightness in preference to lock seaming long practiced, due to the tendency of the lock seam to open with gas explosions. The end joints are closed occasionally with a rolling operation or seam welding, but more generally with some adaptation of the electric arc, maintained automatically, forming an edge weld, Fig. 2. Slight gas leaks that close readily with

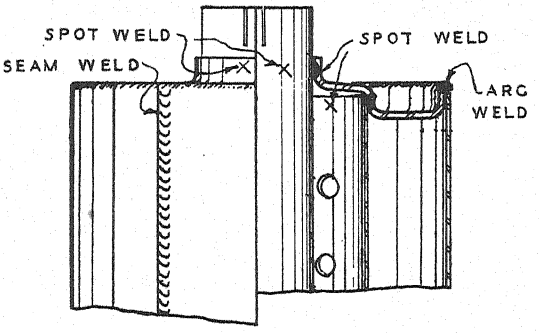


Fig. 2—Typical Muffler

carbon deposits may not be objectionable, but leaks serious enough to permit exhaust noise are not tolerated. Internal parts are preferably so designed and welded that they cannot readily loosen and rattle or be misplaced with gas explosions.

The muffler can be welded to the exhaust tube to avoid all possible exhaust noise. Thin wall sections may be butt welded with the oxyacetylene torch or reinforced with a short sleeve placed around the abutting members and the ends of the sleeve flash welded. The function of such a sleeve is to thicken the section sufficiently that a slight misalignment will not cause a leaky joint. The flash may be readily ground off or covered with paint in the final assembly without the appearance of a rough surface serious enough to be objectionable.

Exhaust Tubing

Exhaust tubing was originally produced by a variety of methods, but the low pressures encountered render the choice of method of small importance except that the tube must be consistently gas-tight and readily withstand bending to the necessary form to properly clear other chassis parts. Much of the tubing now used is rolled, closed and electrically welded at the seam in a single operation.

Fuel Tanks

Terne plate has long been standard material because of the rust-resistant properties of the bright metal coating and because of the ease with which joints may be soldered. Some manufacturers still use the lock seam joint with solder, but due to the saving in solder, it has been found economical to close the joints with the electric seam welder. Tanks failing in the pressure test are rewelded or repaired with solder. The edges of the upper and lower stampings are turned outward, mated together and merely

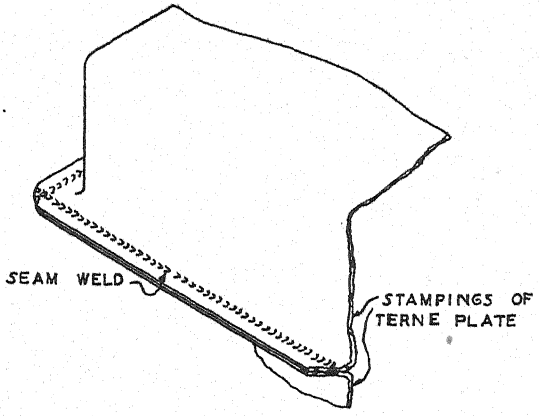


Fig. 3—Section of Fuel Tank

run between the seam welder rolls, Fig. 3. Large production requires elaborate jigs adapted to hold the parts in accurate relation while welding. For smaller production, mating by hand is reliable though less rapid. For very limited quantities, parts intended for seam welding may be joined with the spot welder at close intervals after which the edges are dipped in solder.

The power required for seam welding terne plate to a tight joint is influenced largely by the intervals of current application with relation to the speed of welding. It has been found in practice that the bright metal coating of the terne plate fuses readily between the welded areas in the seam and makes a tight joint that would not be expected in ordinary steel. Welds in No. 18 gage terne plate a little in excess of one eighth of an inch apart readily withstand a satisfactory pressure test. Precision timers used with the seam welder are of considerable value in avoiding excessive rejections and repair

Propeller Shafts

The importance of balance in parts rotating at high speed has considerably influenced the choice of equipment in recent years. Owing to the difficulty of maintaining alignment of mating tube and forging, flash welding has been largely replaced with arc welding. The tubular member is now generally made of flat stock rolled into a tube and welded at the seam with more emphasis placed on the concentricity than pressure-resistant quality, so that tubing made by various processes of welding is now preferred to seamless drawn tubing. In one design in use a few years ago the end forgings were bored for a press fit to the tubing outer diameter, pressed in place, and welded annularly with the metallic arc. In designs in general use at present, the tubing is fitted to a pilot on the forgings at both ends and welded with the automatic metallic arc at one operation, Fig. 4. Bare electrode if not laid too rapidly yields a joint

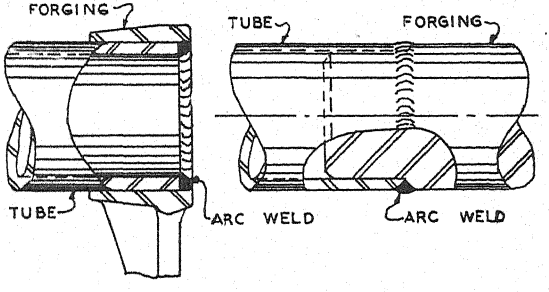


Fig. 4—Propeller Shafts

capable of exceeding the torsional strength of the tubing. For small quantities hand welding, preferably with shielded arc electrode, is equally satisfactory. Most manufacturers insist on a torsion test on the completed assembly as the most practical test for the weld as well as the only test readily applicable to the tube.

Front Axles

Front axles for cars other than with independently slung front wheel mounting are generally of either forged I-beam type or tubular section. The forged I-beam axle is made complete in the forging process although some designs that have not been widely adopted contemplated the use of spring pads arc welded to the I-beam section. In the tubular design spindle bushings as well as spring pads are welded to the tube. The tubular member may be made up of seamless tubing, tubing welded in long lengths and cut to size, or formed in part and welded in approximately the finished shape, the selection of process of course depending upon the economies involved. A typical tubular front axle assembly is shown in Fig. 5.

Rear Axle Housings

Rear axle housings over a long period were built up in right- and left-hand members mating at the differential, each half consisting mainly

of a steel tube with a malleable casting at the inner and outer end riveted to the tubing. Since about 1918 there has been a rapid trend to the pressed steel housing as used at the present time, and nearly all of the development is directly traceable to concurrent developments in processes of welding. Originally the pressed steel housing was made up with the longitudinal seams at the top and bottom of the housing while the differential carrier openings were stamped from the centers of the two sheets somewhat as shown in Fig. 6. Later in order to economize on metal,

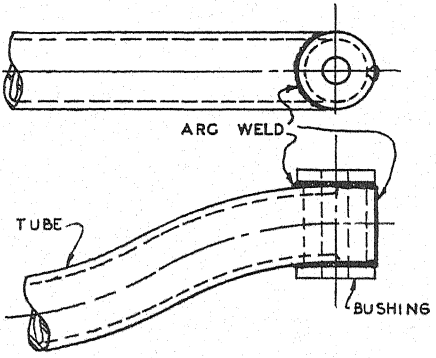


Fig. 5—Tubular Front Axle

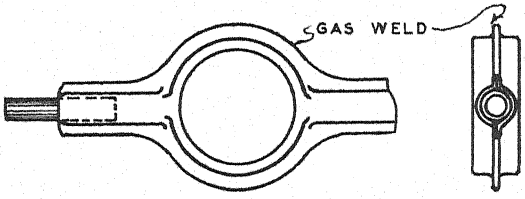


Fig. 6—Early Type of Steel Housing

housings were made of upper and lower identical stampings mated at the front and back, the two stampings forming a full length housing. In some designs, forgings or castings were still used at the outer ends. But at the present time rear axle housings in quantity production rather closely follow the general design shown in Fig. 7. The seams are in front and rear. The mating members are formed from flat blanks approximately as shown in the same sketch. There is one opening through the center with bolt circle reinforcements welded in place to receive the differential carrier in front while the rear side is later covered with a stamping welded or bolted in place. The ends of the housing are flanged in an upsetting operation as indicated in Fig. 10 (lower portion) or have flanged members of steel welded to the ends, as shown in the first sketch of Fig. 7.

Originally most of the welding of the side seams was done with acetylene. About 1922 side seams were very successfully welded with the alternating current arc in a semi-automatic machine while the mating stampings were held rigidly in a jig. Later practically the same operation was performed with the direct current automatic metallic arc.

At about the same time another process, Fig. 10, was developed in which

upper and lower full length stampings are directly welded with current passing from heavy electrodes above and below through the abutting edges at the seam as in flash welding, except that voltage values are held somewhat lower, the pressure is greatly increased and there is little actual explosive flashing. This is desirable in that the flash metal can be cleaned from the inner surfaces of the housing with much less difficulty than in the case of a normal flash weld. This process requires some repair with the arc welder unless careful attention is given to the electrodes and condition of the stampings. Tests indicate a seam as strong as that of the average arc-welded housing. This process is applicable only on a large scale, inasmuch as one unit is calculated for a production of 125 housings per hour. The current required is of the order of about 6000 amp. at 440 v. during an interval of about four seconds while welding, even attaining 8000 amp. for the peak at the last part of the weld during the application of the maximum pressure. Strict regulations from power companies are apt to require a motor generator set to supply single-phase current from a three-phase supply, primarily to avoid the heavy surge on power lines during the peak load.

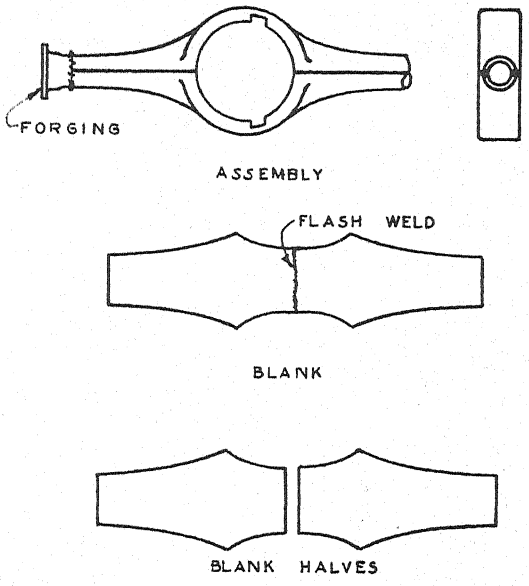


Fig. 7

Another type of housing reverts in principle partly to the housing of several years ago. A tapered tube rolled from flat stock is welded in a continuous automatic metallic arc-welding machine in which the tubes are carried on a chain conveyor under a stationary arc. Later the large end of the tube is flash welded to a flange and the small end to the outer bearing adaptor. The flanged end fits to a cast central member which accommodates the differential carrier. The completed housing then consists of the carrier housing and two tubular members, one right and one left. This type of assembly is shown in Fig. 11.

Adapted more particularly to somewhat lighter press equipment is another method in which the housing is formed in half lengths, Fig. 8. Two mating halves are then flash welded, making the completed housing. This process would be applicable for small production requirements. Of course there are variations applicable to all of the processes herein described.

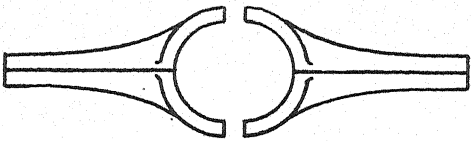


Fig. 8—Assembly Adapted to Light Presses

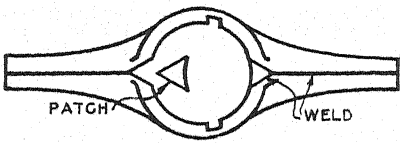


Fig. 9—Scheme Devised to Use Narrow Blank

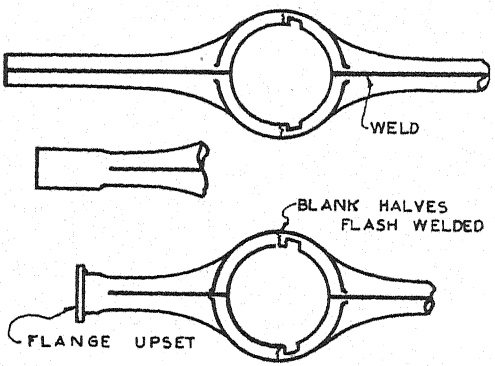


Fig. 10

There is still another method of axle housing manufacture which should be discussed. Originally it was planned to eliminate the side seam weld as far as possible. The material chosen was a piece of seamless steel tubing successively expanded to a larger diameter in the central portion, and swaged to a smaller diameter at the ends. A slotted hole is perforated through both walls of the central portion after which this portion is heated to a temperature in the range of 1200 to 1400°F. A wedge-shaped die is inserted to open up the hole large enough and to a shape to admit a pair of die members which are further spread apart by the insertion of a wedge-shaped die between these last-mentioned die members. The metal is stretched out against the walls of other die members to form the final shape of the central or "banjo" section. A further improvement in the method consists in forming the tube from flat stock perforated in the form-

ing press and so formed that by welding the one side seam with the automatic electric arc the tube is completed with the enlarged central portion with opposed lateral walls perforated. The other operations are carried out much as in the case of the seamless steel tubing. This latter method of manufacture is illustrated with successive forms in Fig. 12.

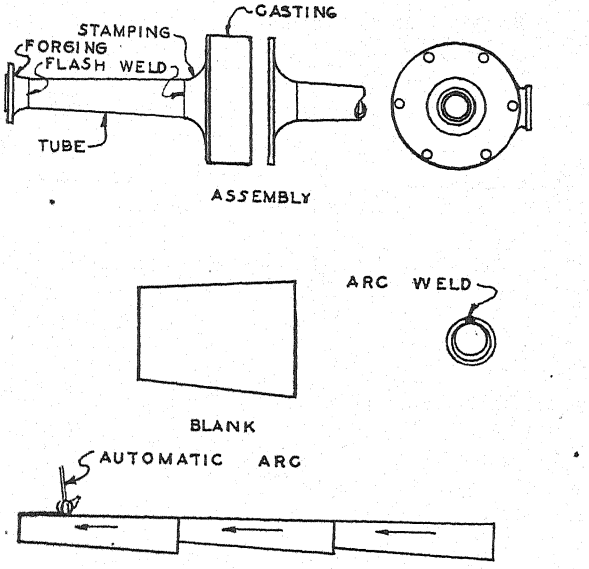


Fig. 11—Method of Feeding Tapered Tubes Under Arc

Nearly all models of modern axle housings are designed to accommodate a heavy bearing enclosed in the thickened walls at the outer tubular ends of the housing and also the brake members. Originally the thickened wall was secured by flash welding a relatively heavy flanged forging to the tubular end. It was discovered later that it was possible by subsequent operations to heat the tubular ends, upset the tube in a bulldozer to the requisite thickness and, at the same time, to form a reasonably thick flange on the end of the tube. Seamless steel, butt-welded, atomic hydrogen welded, flash-welded or arc-welded tubing closed to the full depth of the stock, or closed to the full depth with shielded arc wire, can be readily formed on the bulldozer with three or four forming operations into a homogeneous section with sufficient wall thickness to clean up in machining. In cases in which there is insufficient finishing stock, the use of the metallic electric arc readily adds sufficient stock so that the scrap from such causes is negligible.

The bolting surface reinforcement at the central opening is usually secured with the spot welder, or projection welder in two portions. In later models, the opening on one side is closed entirely by a thin stamped "tin hat" secured with an annular weld applied with the metallic arc.

Spring pads are either forged or formed from flat stock and secured to the tubular wall with the projection welder or with a fillet weld applied by hand, or automatically, for large production.

It is to be borne in mind that in the choice of equipment for axle housing manufacture many factors are to be taken into consideration. Slight improvements in the manufacture of seamless steel tubing, the development in cost of welding operations of one sort or another, the limiting capacities of press equipment, royalties involved, or developments in die design and maintenance, may be sufficient to decide the choice with a margin of less than five cents in the over-all unit cost of production.

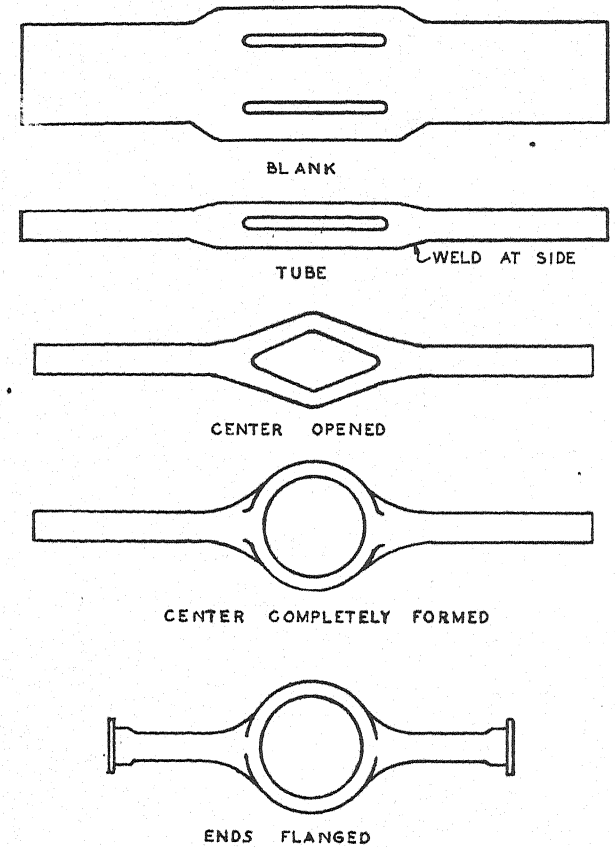


Fig. 12

Fender Parts Assembly

Fenders are universally formed from a fine grade of low carbon steel in nearly all cases of No. 20 U. S. Gage (0.0375 in. thick) and finished very nearly all over with a polishing operation for the purpose of removing surface inequalities, evidences of stretching strains and other objectionable deformities. Polishing marks must even be limited with abrasives of fine size. The reason for such pains in finishing is evident from the fact that defects of small consequence apparent on the bare metal are accentuated to the eye when finished with a thin smooth coat of enamel,

or primer and lacquer. Brazing operations on exposed surfaces cannot readily be covered with enamel because of the tendency of the color to show through the enamel, and inasmuch as a large proportion of fenders are enameled, brazing is considered objectionable unless applied in unexposed places. Repairs at cracked edges, fixing of binding wire ends and such other operations are usually done with the acetylene torch. Reinforcing members, clips, bolting surface reinforcements, reinforcing flanges and other members peculiar to the particular design are nearly always secured with the spot welder, in a few cases perhaps with the projection welder. Other processes of welding in fender work have limited application, confined in general to accessory parts. Precaution is always taken to avoid welds that are apt to distort surfaces to an extent that may suggest broken or irregular contours.

CHASSIS FRAMES

The completely welded chassis frame was predicted as an obvious development immediately following the early application of arc welding in the automotive industry. Frame contours will not readily submit to automatic machines and are subject to frequent changes. Only since about 1930 has there been much development in the application of welding on chassis frames. Frames are now being arc welded on an automatic machine at speeds of 180 to 200 inches per minute.

In one of the more expensive models in about 1931 one or two of the cross-members were formed of two mating members joined with a flash welder to form a rectangular tubular section in the central portion with ends adapted to fit the frame channels. The stock thickness and the length required a heavy welder that nevertheless has apparently justified the cost, and cross-members of tubular cross-sections now are often welded by the flash method. A typical flash-welded section is shown in Fig. 13.

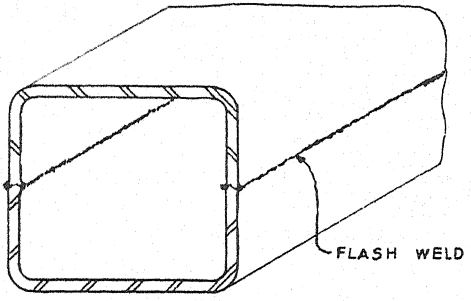


Fig. 13—Frame Cross-Member

Side frame members for one manufacturer are now also being made up of rectangular tubular section with two arc-welded seams, Fig. 15. The length of these members would entail very expensive equipment for flash or butt welding so the design has been adapted for arc welding. Such members are concealed from view, are made of unfinished stock and are treated merely with a thin coat of priming except for whatever paint is applied in the car assembling operation. The finished appearance re-

quired of exposed surfaces is not generally emphasized on frames, so arc welding, flash welding with no finish or acetylene welding is subject to little objection with respect to the surface left unfinished.

A modified rectangular cross-section for frame side members has recently appeared on one of the cars in the lower price field. The section is composed of two members, the upper a flanged inverted U-section, and the lower member a flat strip extending across the bottom of the flanged inverted U-section spot welded at about one-inch intervals to the flanges

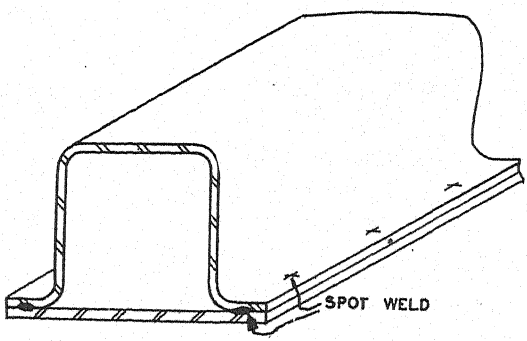


Fig. 14—Recent Frame Side-Member

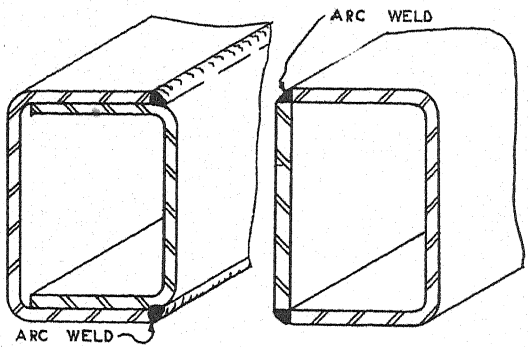


Fig. 15—Section of Typical Frame Side-Member

on both sides (see Fig. 14). Obviously the performance of something over 300 spot welds on so heavy a part as a frame side member would present a considerable problem, so the job is normally done in a special machine in which the welds are made with multiple spot-welder tips hydraulically advanced to welding position and supplied with current and pressure by a commutating device controlling both current and pressure application at tip after tip in rapid succession. Multiple transformers and multiple controlling devices can be applied on such equipment so that all of the spot welds are made in a few seconds.

X-Members

So-called X-members, that is, double central struts between the side members at the center of the frame, are built up in numerous ways. Typical sections are shown in Fig. 16.

An interesting method of roughly controlling the length of arc weld is indicated in Fig. 17. The blank or the overlapping member has the edge relieved except at the areas at which the fillet weld is applied.

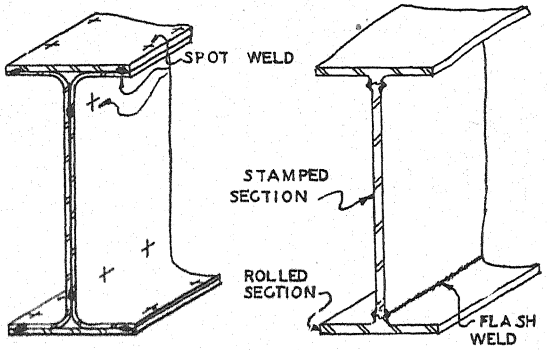


Fig. 16—Section of Typical Frame X-Member

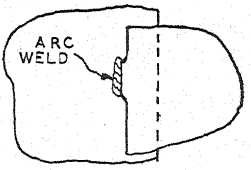


Fig. 17

Though still sometimes assembled wholly or partly with rivets, side- and cross-members are finally welded with either bare or heavily coated electrodes. Projection welding and spot welding would be equally applicable except that the sections are relatively heavy and such welds would almost without exception have to be made with proportionately heavy machines. The wide dissimilarity of the types of joint more readily submits to the metallic arc than to other methods requiring expensive adaptations for each type of section to be joined.

AUTOMOTIVE BODIES

Automotive bodies in America without exception in large quantities are made of high-grade deep drawing steel nearly 100 per cent of No. 20 U. S. Gage (0.0375 in. thick). Contrary to a public impression widely held, due perhaps to a notion that all high-priced cars are made of heavier sections and that low-priced cars are made of metal approaching tin in thickness, practically all automobile bodies are made of the same thickness of stock. Thicker steel adds weight to the car and as yet no means readily applicable has been devised to readily weld thinner metal for body panels either with the arc, atomic hydrogen or with the flash welder. The buying public demands a body with a fully finished surface showing the minimum of visible joints. Therefore, 20-gage steel is standard body sheet material. Exposed parts, such as the instrument panel, garnish moldings, windshield fittings and small accessory parts when made of light sections of steel are welded when necessary to the design by the same methods applicable to other body parts. Reinforcing members added for stiffening the body or

retaining essential parts when not exposed are frequently made of metal of less exacting finish. Butt welding, flash welding, acetylene welding, arc welding, multiple spot welding or brazing may be applied, the choice of method lying in the adaptability of the process and the production requirement.

Large Blanks

The development of large-capacity toggle presses has accentuated the demand for sheets of greater dimensions than can readily be produced at the mill. Sheets from which blanks are subsequently cut are sometimes built up of two or more sections flash welded together. Flash welds as long as 11 ft. in 20-gage metal have been successfully performed. Welds are required to withstand mild forming operations, and have to be roughly finished, at least before being fed to the presses, in order to avoid damage to delicate forming or cutting surfaces.

Body Assembling

With the application of flash welding to body stampings of 20 gage in 1922 a concerted effort was made to eliminate all exposed body seams, formerly the source of unsightly streaks of rust and peeling paint. Almost immediately sedan bodies came to be built with rear corner joints formed in double flash welders both at one operation. There have been important changes but flash welding still is of great importance in body assembling.

Flash-welding machines capable of joining body panels with welds 54 in. long, two at a time, at the rate of 250 assemblies in 8 hr. were in wide use on sedan bodies. In flash welding the greater portion of the time is consumed in placing the stampings in the machine. Necessarily the mating stampings are accurately fitted to jigs before clamping in the welding dies. Clamping with hydraulically operated clamps, air-operated clamps or hand-operated clamps has been tried with varying degrees of success.

Die contact surfaces supplying current to the mating stamping while welding are preferably made of a high conducting material of as high a degree of hardness as may be practicable. Frequent cleaning with brush or an air hose is desirable to avoid clamping particles of flashed metal or dirt between the die surfaces and the metal to be welded, in the first place to get an even flow of current to the metal and, second, to avoid pits and blemishes in the surface which have to be removed by the grinding and polishing operation later. The die contact surfaces have to be dressed occasionally and tend to get out of shape with the frequent application of pressure. It is practical in shapes that have to be very accurately maintained to have on hand a matrix, or master shape, which can be coated with Prussian blue and borne against the die surfaces for test and accurate restoration to form. Such a matrix can be prepared beforehand with reasonable assurance that stampings from dies made to the same drawings will match the matrix contour closely enough. The matrix should be made wide enough to fit both welding die surfaces when pushed together as at the end of the flash weld. The clamping dies can be shaped to the lower welding dies with reasonable assurance for test although a separate mating matrix may be provided for the upper, or clamping dies.

Welding Partly Formed Stampings

Partly formed stampings may be joined by flash welding. After cleaning the surface, in part at least, final piercing, forming and trimming operations may be completed. In this way flash welding may be made applicable to a number of shapes not possible under former methods.

It is to be borne in mind that not all mating stampings can be flash welded. If a plane passed through the line to be welded is very nearly perpendicular to the edges of the two mating stampings for a sufficient distance from the joint to allow room for die grip and also extra stock for flashing, then flash welding is probably feasible. But with the rapid evolution of advanced stream lining there are fewer pairs of mating stampings on bodies of latest style which meet with the normal conditions of flash welding. Also with the all-steel top panel joints are more apt to be at the junction of top and pillar and from back window to rear side window opening.

Acetylene Welded Seams

Such changes of design and method have prompted considerably more acetylene welding and much improvement in the accurate matching of stampings at the edges. In more recent practice the body panels are assembled in very strong rigid jigs and held in very accurate relation with locating and clamping devices. Parts are either tack welded and finished later or completely welded in place. The preferred type of joint is that in which the edges of the mating stampings are turned in slightly so that the finished seam presents the effect of a groove about $^{3}/_{8}$ in. wide and about $^{1}/_{16}$ in. deep with the weld at the bottom. The depression is later filled with solder and finished with file and polishing wheel to the contour of an unbroken curved surface (see Fig. 18).

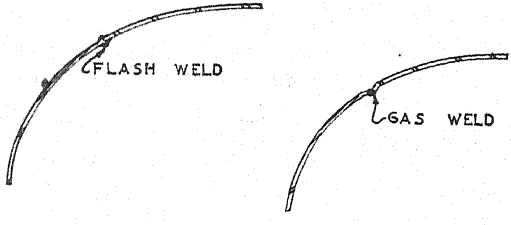


Fig. 18—Section of Typical Body Panel Welds

WELDING GUNS

The all-steel body required the development of the portable spot welder for much of the work that can be advantageously done on the assembly line. An integral welding unit with transformer and actuating mechanism would obviously be too heavy and cumbersome. In present practice extensive use is made of a unit consisting of a suspended or portable transformer unit connected with flexible water-cooled cables to an air-operated or hydraulically operated welding tool, or welding gun, carrying conven-

tional spot welder tips. The welding tool is usually suspended from a balancer and is placed at the point on the line assigned to the particular operation for which the tool is designed. Most body assembly line spot-welding operations can be done with one of three or four special welding tools. For small production in isolated assembly plants one transformer and timing switch may serve as many as three or four tools in turn. The spot welds made by portable welding tools are comparable with those made on stationary machines due to careful inspection and the use of uniformly shaped tips made of some grade of deoxidized copper, which imparts a degree of hardness and resistance to annealing.

Assembling Small Parts

Spot welding and projection welding are widely applied to reinforcing members such as door pillars, corner pillars, wheel housings, upholstery attaching members, seat pans and floor board supporting members. Door frames are made in various ways involving flash welding, arc welding and projection welding principally, after which the surface panels are attached to the frames by spot or projection welding. Door panels with the window opening formed by flash welding mating members at the bottom of the opening and to a cross-member at the top corners have been made. Frequent changes in door shapes would make this questionable as a standard operation, however. There has been also rather wide acceptance of the multiple spot machine hydraulically or pneumatically operated, for standard parts particularly.

AUTOMOTIVE WHEELS

Automotive wheels have changed so rapidly in design from year to year that few welding applications have remained standard over a long period with the exception probably of that of flash welding the joint in the rim. This operation was long standard for steel felloes for wood wheels and demountable rims and also persists even with the drop center rim of the present time. Hand-fed machines attain production figures of 600 rims per hour forming the flash weld on flat stock shaped to a hoop before final forming. Elaborate flash trimmers were developed which cleared the surfaces well enough that no further finishing was required. Such reliance was placed on the rim that the valve stem hole was preferably located at the weld. Within the past few years arc welding was widely used in joining hub members, but more recently the development of the modern type of perforated disc wheel has been designed to avoid exposed welds due to a requirement for plated and otherwise elaborately finished wheels.

Die Maintenance

Welding has been of considerable importance in the maintenance of forming and blanking dies. One manufacturer as a regular procedure fills in cast-iron forming dies with steel applied with the electric arc, afterward finishing the required form over a small area in the arc deposited steel. As the surface wears, the worn areas are again filled in and re-

worked. This plan is especially applicable in areas which form such parts as the belt molding in body dies.

Cutting edges are rebuilt above size with a layer of tungsten steel deposited with the metallic arc and restored to shape by grinding without heat treatment. In some cases cutting edges are built up with the electric arc on bases of low carbon steel, hardened, ground to shape and mounted on the base in the manner of blocks entirely made of tool steel. This type of die is effective for short runs if the material to be blanked is not too heavy, otherwise the soft steel base may deform rapidly. An advantage noticeable in some cases is that of being able to stake the cutting edge outwardly without drawing the temper of the tool steel face laid with the arc. This latter method presents a means of building up cheap dies for short runs.

Repair of blanking die-cutting edges with the atomic hydrogen arc is meeting with considerable success in some shops because of the assurance with which it may be applied to almost any alloy steel without damage or fear of failing to make a uniform deposit of metal. It is desirable to have on hand rods of metal adapted to fill in areas of the same analysis as the block in repair. After welding, the entire block can be heat treated and returned to service with cutting edges built up, extended or completely restored.

CHAPTER 41A

INDUSTRIAL PIPING*

Introduction, Welding Processes Most Commonly Used, Qualification of Procedure, Qualification of Welding Operators, Types of Welds and Welding Grooves for Pipe and Fittings, Pipe End Clearances, Preparation of Welding Faces, Welding Electrodes and Rods, Clearance for Welding, Lining Up and Tacking, Number of Passes or Layers, Cleaning, Direction of Welding, Preheating and Stress Relieving, Welding Fittings, Field Inspection and Testing.

Introduction

INDUSTRIAL piping, as discussed in this chapter, is considered to include: (*a*) high-pressure, high-temperature power plant piping; (*b*) intermediate- and low-pressure power plant piping; (*c*) process piping; (*d*) oil refinery piping; and (*e*) heating systems piping.

The progressive increase in the pressures and temperatures utilized in steam power plants, process industries and oil refineries has over the past several years focused attention on the design of piping systems as a whole and on the design of joints in particular. The original flanged and bolted joint has undergone many modifications as designers have sought to incorporate improvements with the view to adapting it to the increasingly severe demands placed upon it.

There are in service, today, flanged and bolted joints at the prevailing high pressures and temperatures, but such joints are, without exception, costly. Of even more importance is the fact that such joints are not sufficiently trouble-free to give the desired continuity of service. The factors which make them troublesome, to some extent at least, are (1) creep of the bolting material under the prevailing bolt stresses and temperatures, (2) distortion of the mating faces of the flanges, and (3) deterioration of the gasket material, where gaskets are used.

In addition to the high-pressure, high-temperature piping, there are a great many moderate-pressure and temperature piping systems where continuously tight joints are especially desirable and where welding is taking the place of screwed or flanged joints. An example is turbine

* Prepared by a committee consisting of D. H. Corey, Detroit Edison Company, *Chairman;* R. W. Clark, General Electric Company; F. C. Fantz, Midwest Piping & Supply Co.; V. Forgett, Air Reduction Sales Co.; C. A. Kelting, Consolidated Edison Co. of New York; E. H. Krieg, American Gas & Electric Service Corp.; D. E. Roberts, The Linde Air Products Co.; H. Weisberg, Public Service Electric and Gas Company; J. W. Wilson, Bureau of Marine Inspection & Navigation.

oil piping, where a leaky joint constitutes a distinct fire hazard. Permanent tightness of joints such as available in welded construction is essential in services which are comparatively inaccessible after installation. Further advantages resulting from the elimination of flanges are a decrease in the weight to be supported and a decrease in the cost of insulating the piping.

The continued and even more general acceptance of welding as a reliable method of joining pipes and fittings will require careful observance of the following general rules: (*a*) The base materials either must be weldable without special precautions or, if not, the necessary precautions must be known and followed. (*b*) The joint design must be such that the joint is accessible to the welding operator. (*c*) The welding procedure that is employed must be one that has been investigated and found to produce welds with the desired physical properties. (*d*) The welding operators must have been trained to follow that procedure and must be supervised to insure that they do follow it within definite limits.

The base materials covered by this chapter are rolled, welded, forged and cast plain carbon steels with a carbon content not in excess of 0.35% and also carbon-molybdenum steels.

Welding Processes Most Commonly Used

The welding processes most commonly used in the fabrication of industrial piping are the metal arc and the oxyacetylene processes. This chapter as written is based on these two processes. Other methods are occasionally used, particularly in shop fabrication, but these other methods in general utilize special joint designs and welding procedures. Fundamentals of these other processes are discussed elsewhere in this Handbook.

All of the pipe and fitting materials mentioned above can be and have been welded satisfactorily with both the metal arc and the oxyacetylene process. It seems safe to say that any industrial piping job can be done by either process and that the choice in any particular case may depend on personal preference or the degree of experience of the available welding operators with one or the other of the two processes. It thus appears that no clear-cut distinction can be drawn between the advantages of metal arc welding and oxyacetylene welding for different jobs. However, the oxyacetylene process has been employed extensively on small diameter, thin-walled tubing such as used for instrument piping. Likewise, there seems to be a general tendency to specify oxyacetylene welding for work where the clearances around the joints are small, as in superheater and economizer tube work, although there are numerous instances where the metal arc method has been used just as successfully under these conditions. For the larger joints which must be welded in a fixed position, requiring vertical and overhead welding, and particularly for carbon-molybdenum steel, the metal arc method has been used more generally.

Qualification of Procedure

For a given base material, the quality of a welded joint made by the metal arc or oxyacetylene process will be determined by the specific welding

procedure used and by the ability of the welding operators to follow that procedure. The first step in welding, therefore, should be the adoption of a definite welding procedure. The procedure should be outlined, preferably in specification form.

Recommended forms of procedure specifications may be found in an appendix to any of the following publications: The A.W.S. Tentative Standard Qualification Procedure, the A.S.A. Code for Pressure Piping, the A.S.M.E. Code for Power Boilers, the A.S.M.E. Code for Unfired Pressure Vessels. For all of the materials covered in this chapter, three separate procedures may be required: (1) for plain carbon steels whose carbon and manganese contents are sufficiently low that preheating is not required; (2) for plain carbon steels whose carbon and manganese contents are such that preheating is required; (3) for carbon-molybdenum steels. For specific information as to the number of test welds, number and type of test coupons, and test results required, reference should be made to the Code covering the particular work for which the procedure is to be qualified. However, the A.W.S. Tentative Standard Qualification Procedure (Chapter 29 of this Handbook) has now been adopted by practically all regulatory bodies concerned with the piping included in this chapter.

Qualification of Welding Operators

Having established that a given procedure is satisfactory, comparatively simple tests may then be used for the qualification of the operators. These tests are designed to determine the ability of welding operators to make sound welds when using a specified procedure. Again, reference should be made to the appropriate Code for details. The A.W.S. Tentative Standard Qualification Procedure has been adopted by both the A.S.A. Code for Pressure Piping and the A.S.M.E. Code for Power Boilers. However, due to the fact that revisions of these various codes are not made simultaneously, there may be minor differences in the requirements.

Types of Welds and Welding Grooves for Pipe and Fittings

(*a*) *Butt Type Welded Joints.*—The most common type of joint employed in the fabrication of welded piping systems is the circumferential butt joint. It is the most satisfactory from the standpoint of stress distribution. Its general field of application is pipe-to-pipe, pipe-to-valve and pipe-to-fitting joints. Butt joints may be used in all sizes, but a design which employs fillet-welded joints can often be used to advantage for the small sizes, such as 2 in. and smaller.

While there are no universally accepted welding grooves, those shown in Fig. 1 are now considered, for all practical purposes, as standard for industrial piping. These grooves appear in the American Standard for Steel Pipe Flanges and Flanged Fittings, A.S.A. B16e-1939, and in the American Standard for Butt Welding Fittings, A.S.A. B16.9-1941, as recommended practice. Welding fittings purchased from stock are furnished with these bevels, and much of the piping fabricated since the publication of A.S.A. B16e-1939 has been furnished with one or the other of these "recommended standard" grooves. For oxyacetylene welding, some

users prefer the 75° or even a 60° included angle groove for all pipe thicknesses, and some, particularly those using the "fore-hand" method, recommend a 90° included angle groove.

(*b*) *Backing Rings.*—The term "backing ring" is applied to a ring-shaped structure which is fitted to the inside surface of the pipe at a joint prior to welding. It may be either a plain flat strap rolled to fit inside the joint, a forged or pressed shape with or without projections or a circumferential rib which spaces the two pipe ends the proper distance apart, or a machined ring of any desired cross-section. Its function is to assist the operator in securing complete penetration of deposited weld metal to the inside surface of the pipe without burning through, to prevent globules of spattered weld metal and slag from entering the pipe at the joint, and to prevent the formation on the inside of the joint of irregular shaped masses of metal, commonly called "icicles" or "grapes."

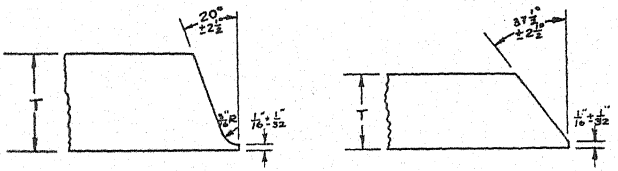


Fig. 1—Recommended Forms of Bevels for Butt-Welded Joints

A further benefit derived from the use of backing rings is that they assist materially in securing proper alignment of the pipe ends. They are used extensively in the field welding of piping for severe service conditions, where internal cleaning cannot be carried out subsequent to welding, and where the elimination of weld spatter is essential for the protection of valves, turbine blading, gears, etc. They are not ordinarily used in shop fabrication, and where internal cleaning is to be done they are often removed after weld completion.

Figure 2 illustrates several types of backing rings which have been used, and also a special type of pipe end preparation in which a lip is formed and subsequently rolled inward, designed to serve as a substitute for a separable ring. Backing rings should be made from steel which is readily weldable, and are usually of plain low carbon steel, even for services where the pipe itself is of carbon-molybdenum steel.

(*c*) *Intersection Type Welded Joints.*—Intersection joints, such as medium and large size welded tees, laterals, wyes, etc., are usually the most difficult welds encountered in the fabrication of industrial piping systems. Machines for flame cutting and beveling the header openings and the branch ends are available, but not in general use. Cutting and beveling is usually done manually with an oxyacetylene cutting torch. Figure 3 illustrates two forms of preparation for 90° intersection joints. In one the header opening is sufficient to permit insertion of the branch, and the,

header opening only is beveled. In the other, the header opening is equal to the inside diameter of the branch, and the branch only is beveled. The latter form permits the use of a specially shaped backing ring if desired. A third form, in which both the header and branch are beveled, has largely been superseded by one or the other of the two illustrated.

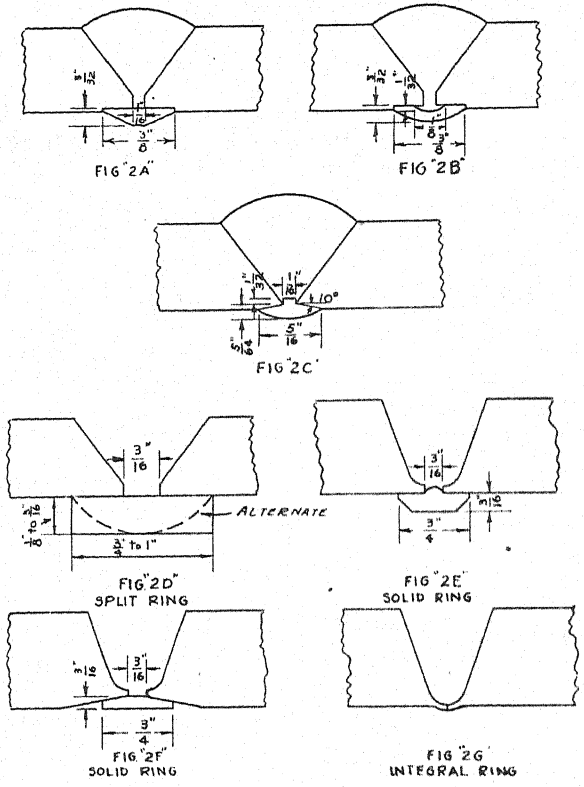


Fig. 2—Types of Backing Rings

The intersection of two pipes at an angle of 45° or less produces a condition at the crotch of the intersection which makes it difficult, if not impossible, to secure the degree of penetration and soundness of weld deposit that is considered essential for severe service conditions. Such intersection welds should be avoided for services where the pressure exceeds about 125 psi. Piping should be designed, wherever it is at all possible, so that all intersection joints, regardless of angle, can be made under shop conditions—that is, where the work can be turned.

(*d*) *Weld Reinforcement.*—Butt joints should be reinforced with weld metal in excess of the net throat dimension by at least $^1/_{16}$ in. The reinforcement should be so built up that there is a gradual increase in thick-

ness from edge to center. Excessive reinforcement should be avoided, as it may introduce undesirable stress concentrations.

Intersection joints for high-pressure service require supplementary reinforcement to offset the weakening effect of the opening made to receive the outlet and to relieve the joint, partially at least, of bending stresses which may be imposed on the outlet in service. Sufficient reinforcement must be provided so that the resistance to bursting of a section of the header containing the outlet is equal to that of the original pipe.

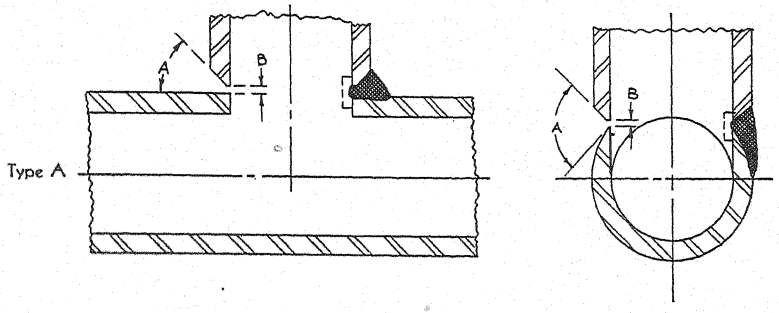


Fig. 3A

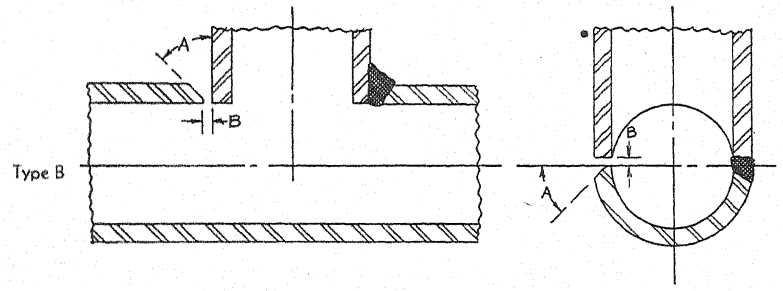


Fig. 3B

Angle A to be not less than 45° for any wall thickness of pipe. B to be not less than $1/16$ in. or more than $1/4$ in.

Fig. 3—Acceptable Types of Preparation for 90° Branch Connection

Rules for the reinforcement of intersection joints are given in the A.S.A. Code for Pressure Piping, and reference should be made to that Code for specific information as to the necessity for reinforcement and the amount required. Figure 4 illustrates two of the most common types of reinforcements.

(*e*) *Fillet Type Welded Joints.*—The general field of application for circumferential fillet-welded joints is pipe-to-pipe, pipe-to-valve and pipe-to-socket fitting joints, all in small sizes—that is, about 3 in. and under. This type of joint is particularly well suited to these applications because of the fact that it accomplishes in small-size pipes, without backing rings

and without restricting fluid flow, what is accomplished in large size pipes by the use of backing rings. The fact that a backing ring in small size pipes occupies an appreciable part of the internal pipe area precludes its general use.

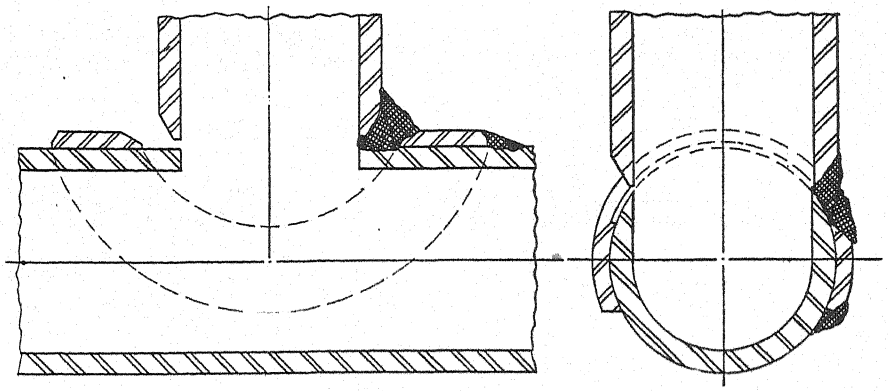


Fig. 4A—Strap Reinforcement with Type "A" Preparation

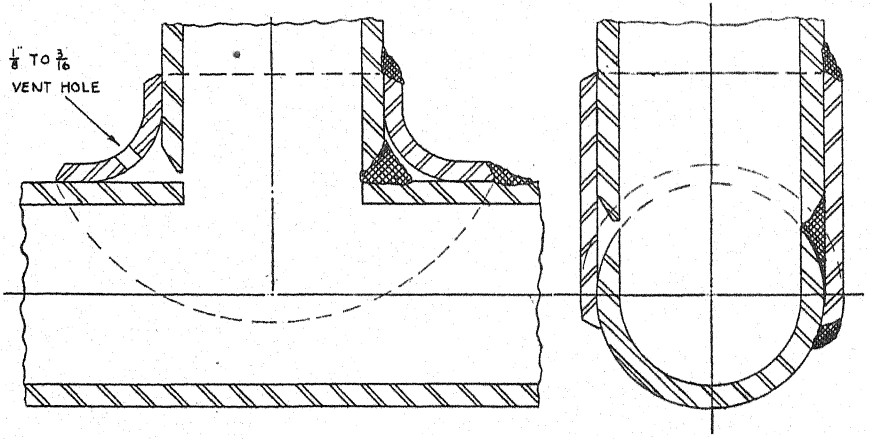


Fig. 4B—Saddle Reinforcement with Type "A" Preparation

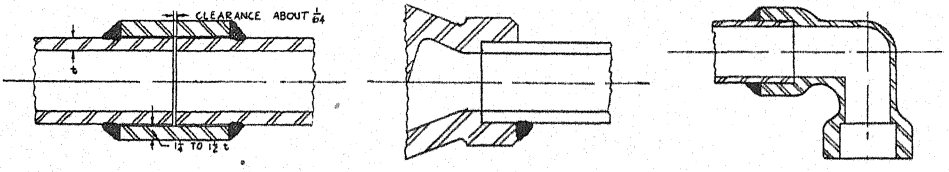


Fig. 5—(A) Welded Sleeve Coupling. (B) Socket Detail for Small Welding End Valve. (C) Socket End Welding Elbow

Figure 5 illustrates three typical joints of this type. The welded sleeve coupling is a development from the conventional threaded coupling and serves essentially the same purpose. Socket welding fittings are available in all of the usual forms, such as ells, tees and crosses. For standard dimensions of such fittings, refer to A.S.A. Proposed American Standard for Steel Socket-Welding Fittings, A.S.A. B16.11. Figure 6 illustrates socket and fillet weld dimensions as recommended in the A.S.A. Code for Pressure Piping.

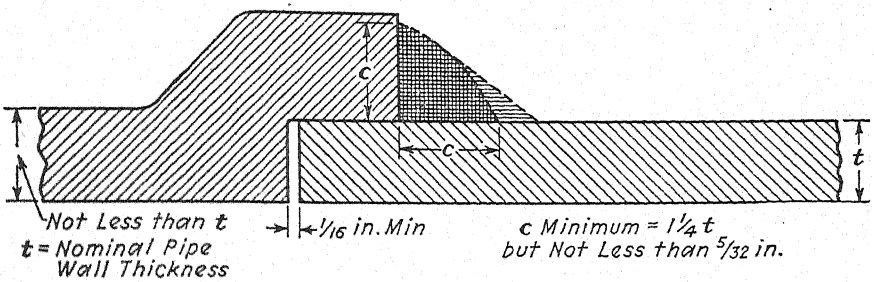


Fig. 6—Fillet Weld Dimensions

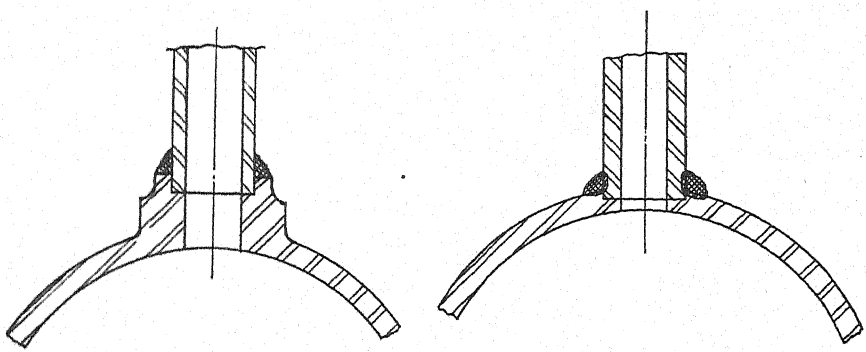


Fig. 7A **Fig. 7B**

Fig. 7—Typical Nozzle or Pipe Connections for Instrument and Small Size Connections

(*f*) *Seal-Welded Joints.*—The function of a seal weld is to secure fluid tightness of a joint where the strength is provided by other means. Experience has shown that the heating accompanying a seal-welding operation tends to destroy the tightness of most forms of mechanical joints. The requirement of securing adequate penetration of the two pieces being joined by the seal weld and at the same time keeping the heating of the parts to a minimum, can best be met by using small diameter electrodes or rods. Ample time for cooling should be allowed between layers to prevent overheating of the work.

Seal welding of pieces of markedly different cross-sections requires extreme care and a high degree of skill to secure equal penetration of the two

unequal sections. There is danger of burning through the thinner section due to overheating, or failing to fuse the deposited metal to the heavier section due to underheating.

(*g*) *Thermometer, Instrument, Drip, Drain and By-Pass Connections.*—Two typical welded connections of this class are shown in Fig. 7. In one, a pad or boss is provided, either built up by welding or cast integral in the case of cast fittings. In the other, no boss is provided, and the large pipe is simply drilled and spot-faced or counterbored to provide a flat seat or socket for the small pipe. Both types require only a simple fillet weld for completion.

(*h*) *Pipe Hangers.*—When lugs, plates, angle clips, straps, etc., which are used as part of a hanger assembly for the support of piping, are welded directly to the pipe, care should be taken to see that the design of the attachment is adequate for the load. Such welding should be done only by operators qualified to weld the piping joints.

Pipe End Clearances

In positioning two pipe ends for groove welding, a clearance between the ends of $^1/_{16}$ to $^1/_4$ in. is ordinarily allowed. The purpose of this clearance is to permit full penetration of the weld metal to the inside surface of the pipe. For arc-welded joints made without backing rings, the clearance should tend toward the low value given above to minimize the danger of burning through. With backing rings $^1/_8$ in. thick, clearances up to and including $^3/_{16}$ in. are commonly used. With thicker backing rings, clearances up to $^3/_8$ in. are reported to be in use.

Clearances which have proved satisfactory for oxyacetylene welded joints made with or without backing rings are given in Table 1.

Preparation of Welding Faces

All welding faces and the adjoining pipe surfaces for a distance of at least $^1/_4$ in. from the edge of the welding groove should be free from rust, scale, paint, oil and grease, as their presence makes it difficult, if not impossible, to secure complete fusion to the base metal and a sound weld deposit. Welding ends which have been given a light coat of a preservative which will not affect the quality of the finished weld, need not have that coat removed.

Welding Electrodes and Rods

(*a*) *Electrodes for Metal Arc Welding.*—Metal arc welding of industrial piping is done exclusively with covered electrodes. For a classification of the various types of electrodes available, refer to the A.S.T.M. "Tentative Specifications for Iron and Steel Arc-Welding Electrodes: A233–42T," prepared jointly by the A.W.S. and the A.S.T.M. (See Chapter 27 of this Handbook.) For the low carbon steels, electrodes of the E6010, E6011 or E6020 class should be used, the specific choice depending on whether the pipe is welded in the fixed position or is rolled, and on whether the welding current supply is d.c. or a.c. When weld metal having a tensile strength of 70,000 psi. or greater is desired as is sometimes the case in welding the higher carbon steels and as is usually the case in welding carbon-molybdenum steels, electrodes of the E7010, E7011

or E7030 class should be used. Inasmuch as the classifications in the above specification are on the basis of tensile properties, position of work and nature of the welding current, it is important, in ordering, that the composition carbon, or carbon-molybdenum, as well as the class, be specified.

When plain carbon steel pipe and low alloy steel valves or fittings are to be joined, as is often the case, plain carbon steel electrodes are satisfactory. These will develop at least the full strength of the pipe, and will probably exceed that strength considerably by virtue of becoming enriched by fusion with the low alloy steel. Choice of electrode size is largely a matter of conditions under which the work is to be done. For fixed position work, electrodes $^5/_{32}$ in. in diameter, or smaller, are most commonly used. The $^5/_{32}$-in. size is about the largest which can be handled successfully in a vertical or overhead position by most welding operators.

(*b*) *Rods for Oxyacetylene Welding.*—Filler metal for oxyacetylene welding of pressure piping should conform to A.W.S.-A.S.T.M. Specification A251–42T, Classification No. 60.

Rods are available for welding plain carbon and carbon-molybdenum steels, but pending the publication of the new Specification referred to above, there is no classification corresponding to that for arc welding electrodes.

Clearance for Welding

Adequate clearances from walls, ceilings and floors should be provided whenever welds are to be made in the field. This is necessary not only to permit the welding operator to reach the joint, but also to permit him to be in position to observe all parts of the weld. A minimum clearance of 6 in. is suggested for pipe sizes up to and including 4 in. As the pipe size increases the minimum clearance should increase up to about 10 in., which is probably sufficient except in corners, in which case the clearance between pipe and one wall must be sufficient to allow the operator to get into and work from the corner.

Lining Up and Tacking

Before welding, the pipe or fitting ends must be carefully lined up. As mentioned in a previous paragraph, backing rings assist materially in securing good alignment. If the two pieces to be joined have the same internal diameter, the backing ring brings the bore of the two pieces into alignment, irrespective of wall thickness. This is desirable from the standpoints both of fluid flow and ease of depositing the first bead or layer of weld metal. When backing rings are not used, the two pipes or fitting ends are often secured in a fixed position relative to each other by means of an external clamp. Several types of clamps are available for this purpose.

When the joint is lined up, tack welds, in the form of short welds spaced at regular intervals around a joint, are made prior to actual welding of the joint, the purpose being to maintain the joint alignment which has been established and thereby permit the removal of any external fastenings which have been used for this purpose and would interfere with the complete welding of the joint. Tack welding also permits handling the pipe

Table 1—Spacing and Tacking Details for Oxyacetylene Welded Piping and Fittings

Standard Pipe Schedule 40, ASA B36.10″				Extra Heavy Pipe Schedule 80, ASA B36.10″			
Pipe Size	Spacing Between Pipe Ends,* In.	Number of Tack Welds for Proper Strength and Alignment	Average Length of Tack Welds, In.	Pipe Size	Spacing Between Pipe Ends,* In.	Number of Tack Welds for Proper Strength and Alignment	Average Length of Tack Welds, In.
1/2	1/16	2	1/4	1/2	1/16	2	1/4
3/4	1/16	2	1/4	3/4	1/16	2	1/4
1	1/16	2	1/4	1	1/16	2	1/4
1 1/4	1/16	2	1/4	1 1/4	1/8	2	3/8
1 1/2	1/16	2	1/4	1 1/2	1/8	2	3/8
2	1/16	2	3/8	2	3/16	2	1/2
2 1/2	1/8	2	3/8	2 1/2	3/16	4	1/2
3	1/8	4	1/2	3	3/16	4	1/2
4	1/8	4	1/2	4	3/16	4	5/8
5	1/8	4	1/2	5	3/16	4	5/8
6	3/16	4	5/8	6	1/4	4	5/8
8	3/16	4	5/8	8	1/4	6	3/4
10	3/16	4	5/8	10	1/4	6	3/4
12	3/16	6	3/4	12	1/4	6	3/4

* Spacing is that recommended for "back-hand" welding. For "fore-hand" welding, it is recommended that the spacing for 6-in. to 12-in. pipe, inclusive, be increased by 1/32 in. over the values in the table.

after setting up and before welding. A rule which is often used in establishing the lengths of tack welds in arc welding is that the lengths should be twice the thickness of the parts joined. Tack weld data for gas welding are given in Table 1. The same electrodes or rods should be used for making tack welds as are to be used for completing the joint. Tack welds should be thoroughly cleaned before being welded over, and thoroughly fused into the main weld.

Number of Passes or Layers; Cleaning; Direction of Welding

The number of passes required in making a pipe weld varies with the wall thickness of the pipe and the position of the pipe when welded. The effect of wall thickness is obvious. When the work can be rolled or when the pipe is in a fixed horizontal position, a layer of metal is deposited across the full width of the welding groove during each pass. (When nearing the top of the groove in heavy wall pipe, the layers are sometimes deposited in the form of two or three overlapping passes, each pass extending one-half or one-third of the distance across the groove.) With the pipe in a fixed vertical position, deposition as described above is not possible. Instead, the metal is deposited in the form of a series of "stringer beads." In arc welding pipe that is either rolled or in the fixed horizontal position, there is usually approximately one layer or pass for each 1/8 in. of pipe wall thickness. In gas welding by the "back-hand" method under the same conditions, there is usually one layer or pass for wall thicknesses up to 3/8

in., two for wall thicknesses $^3/_8$ to $^5/_8$ in., three for wall thicknesses $^5/_8$ to $^7/_8$ in., and four for wall thicknesses $^7/_8$ to $1^1/_8$ in. In gas welding by the "fore-hand" method, the metal is usually deposited in a single pass. In welding pipe in the fixed vertical position, practice varies widely. The procedure specification as to the number of beads to be deposited for each wall thickness should be followed closely.

Each layer of deposited weld metal should be thoroughly cleaned prior to the deposition of the following layer. Wire brushing, especially when done with a power-driven brush, is effective in removing the slag deposited by covered electrodes used in arc welding. Surface defects which will affect the soundness of the weld should be chipped out. The surface of the deposited metal and of the faces of the base metal should be prepared for the following layer by removing humps and sharp corners or grooves which might otherwise be difficult to fill without risk of slag inclusions. In welding for severe service conditions, such cleaning is often done with power-operated chipping tools. In arc welding, the cleaning is often done by a helper, as the arm fatigue resulting from operation of the cleaning tools makes it difficult or impossible for the operator to manipulate the electrode to give the best results.

There is no universally accepted or recommended direction of welding on pipe in a fixed horizontal position. In metal arc welding, the preferred direction seems, usually, to be from the bottom upward. However, considerable welding, especially of thin or medium thickness pipe, is done in the opposite direction. Ordinarily more metal per layer is deposited when welding upward, and the requirement of having the layers thin enough to undergo complete grain refinement must be watched. On the other hand, downward welding probably requires a higher degree of manual skill to secure adequate fusion with the side walls and to avoid trapping of slag. In oxyacetylene welding by the "back-hand" method, the weld is usually started at the top of the pipe and finished at the bottom. In oxyacetylene welding by the "fore-hand" method, the opposite technique is usually used, that is, starting at the bottom of the pipe and working upward to the top.

Repair of Welds

When a weld is to be repaired, the defect should first be removed by chipping, machining, flame gouging or flame cutting. After removal of the defect, the surface upon which the repair weld is to be deposited should be so shaped and cleaned that a sound weld deposit may be obtained. If preheating was required in making the original weld, it should be employed also in making the repair. Should there be general sweating of a weld, no attempt to repair it should be made. The entire weld should be removed and the joint rewelded.

Preheating and Stress Relieving

Preheat, by definition, is heat applied prior to welding or cutting operations. The purpose of preheating the base metal prior to welding is to decrease the temperature difference between the weld metal being deposited and the base metal, so that the cooling rate of the deposited weld metal will be retarded. The necessity for preheating depends upon the composition and the thickness of the material being welded. The composition affects

the ability of the steel to withstand the rapid cooling from above the critical temperature, which is associated with welding, without the formation of cracks or of an undesirable martensitic grain structure adjacent to or within the weld. The thickness is a factor, because it determines the degree of heating of the base metal by the heat input of the welding operation itself. Since preheating, when required, is to prevent the formation of cracks or of a hard, brittle zone susceptible to cracking, due to too rapid cooling, it follows that the preheat temperature must be maintained throughout the welding operation. In some cases, the welding operation itself will maintain the required temperature.

Stress relieving of a pipe weld consists of heating uniformly a circumferential band containing the weld at the middle. The A.S.A. Code for Pressure Piping specifies that the width of band shall be not less than twice the width of the weld, the width of the weld being considered to be the width of the widest part of the welding groove. This band should be heated to a temperature of 1100 to 1250°F., held at that temperature for a period which is equivalent to one hour per inch of thickness for plain carbon steels, two hours per inch of thickness for carbon-molybdenum steels, but never less than one-half hour, and then allowed to cool slowly in still air

This treatment is designed to allow residual stresses set up by the welding operation to be relieved by plastic flow and to change martensitic and troostitic grain structures to sorbitic structures. The result is an increase in the ductility and toughness of the joint.

(*a*) *Code Requirements for Preheating.*—The A.S.A. Code for Pressure Piping requires that welded joints in carbon-molybdenum steel of any thickness be preheated adjacent to the welding zone to a temperature of not less than 400°F. This preheating must be uniform and the temperature must be maintained during the actual welding operation. Preheating is not required, by this Code, for plain carbon steels whose carbon content does not exceed 0.35%.

(*b*) *Methods Employed in Preheating.*—Preheating may be accomplished by any one of several methods. The simplest, of course, is torch heating. It is recommended, however, that this method be used only for pipe which is of sufficiently small diameter to result in a reasonable degree of temperature uniformity around the circumference and where the heat input due to welding is such that no supplementary heating is required to maintain the desired temperature. Where supplementary heating is required, as is usually the case, it is usually accomplished by electric heating elements wrapped around the pipe ends or by muffle type furnaces burning oxy-propane or fuel gas-air mixtures and designed to fit around the ends, leaving an open space at the joint for welding. In the case of electric heating, the coils may be designed to heat by conduction and radiation or by induction. In the latter case, the heating current is usually switched off during actual welding, as the induced current in the pipe interferes with weld metal deposition.

(*c*) *Code Requirements for Stress Relieving.*—The A.S.A. Code for Pressure Piping requires stress relieving of joints in plain carbon steel having a carbon content not exceeding 0.35%, when the nominal wall thickness is $^3/_4$ in. or more. That Code requires stress relieving of joints in carbon-molybdenum steel when the wall thickness is $^1/_2$ in. or more.

The A.S.M.E. Code for Power Boilers requires stress relieving of both plain carbon and carbon-molybdenum steels included by the scope of that Code wherever the wall thickness exceeds $^3/_8$ in.

(*d*) *Methods Employed in Stress Relieving.*—The most satisfactory method of stress relieving is by heating in a furnace, and this is done whenever practical. However, this method is, in general, suitable only for the relief of shop-welded sub-assemblies. Methods which have been used in the field for circumferential butt welds are electric heating by induction with low frequency (60 cycles or less) electric current, electric heating by conduction and radiation with coiled heating elements wrapped around the joint, flame heating with metal or refractory furnaces of the muffle type designed to fit around the joint and burning an oxy-propane or fuel gas-air mixture.

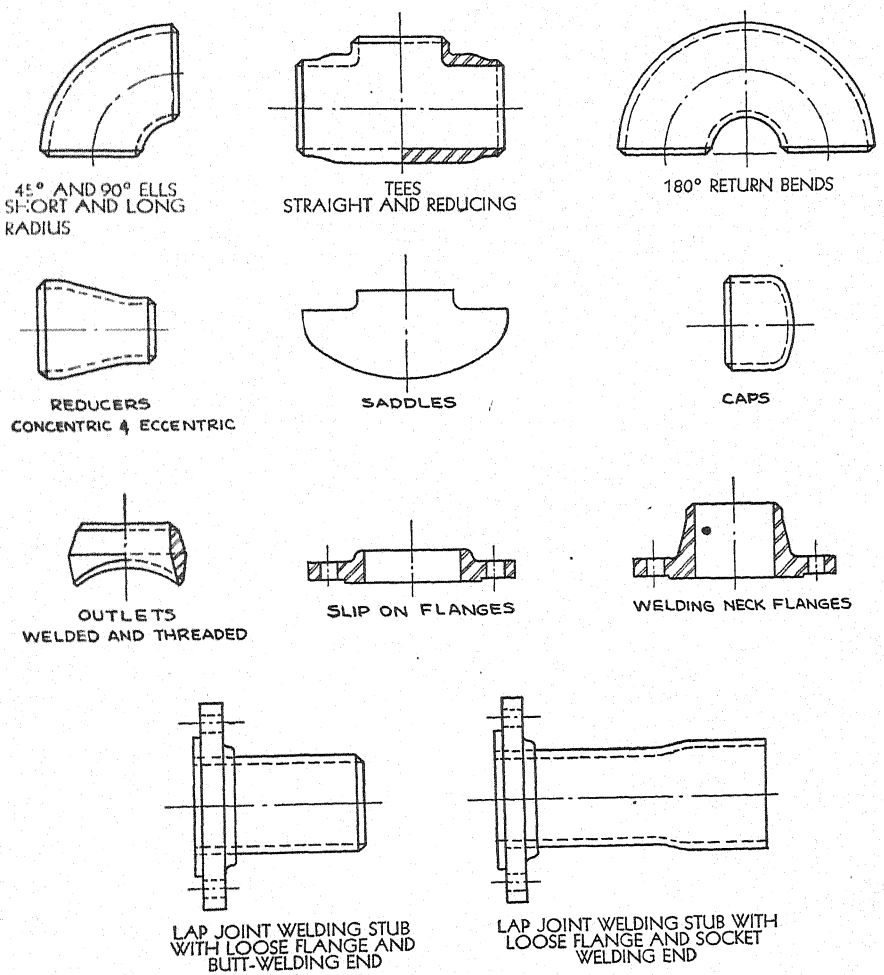


Fig. 8—Typical Fittings and Flanged Connections Designed for Welding

Welding Fittings

Manufacturers have kept pace with welding designs by providing a line of fittings designed especially for welding and made of materials and wall thicknesses to meet most of the A.S.A. schedule numbers now in general use. They are of the plain end type, beveled for groove welding, and also of the socket or recessed type for fillet welding. Some typical types of these fittings and flanges are shown in Fig. 8.

Flanges for services up to 300 psi. may be of the slip-on type. For high pressures they should be either the butt-welding type which are welded direct to the end of the pipe or the lap-joint type for use with stubs welded to the ends of pipe. Elbows are regularly made in 90 to 45° styles. Reducers are available in both the concentric and eccentric types. Tees are available in most sizes and in some reducing combinations. A wide variety of welding heads is available.

Field Inspection and Testing

Field inspection ordinarily consists simply of visual observation by a responsible welding foreman or inspector. An important duty of an inspector is the inspection of the joint prior to actual welding, to make certain that the joint has been properly fitted. The alignment of parts, fit of the backing ring and spacing of the pipe ends are especially important. No welding operator can produce a thoroughly sound joint where the parts to be welded have been poorly fitted.

Inspection during welding ordinarily consists of occasional observations to see that the welding procedure specification is being followed, particularly as to welding current, number of passes being deposited and cleaning between passes. Inspection following welding is for general appearance of the weld, noting the amount of reinforcement and presence or absence of undercutting, and making certain that, for Code work, the welds are stamped with the welding operator's symbol and the A.S.M.E. Boiler Code symbol stamp for pressure piping where and when required.

Welded industrial piping is usually tested hydrostatically upon completion of the work. Piping within the scope of the A.S.M.E. Code for Power Boilers should be tested at $1^1/_2$ times the maximum allowable working pressure, and while subject to this pressure, all welded joints should be given a hammer or impact test. Piping within the scope of the A.S.A. Code for Pressure Piping should be tested hydrostatically in accordance with the requirements of the section of the Code covering the specific class of service involved. The hammer or impact test of the welds is not a requirement, in this Code, but is a matter for agreement between the purchaser and the contractor.

Inspection and testing, either in whole or in part, are frequently carried out by a qualified inspector regularly employed by an insurance company. Inspection of this type, that is, by a representative of an insurance company, forms a part of some specification requirements.

Some forms of non-destructive tests, such as Magnaflux, X-ray, and Gamma-ray, have been used in the inspection of welded joints in piping systems where the service conditions are severe. Their use thus far, however, has been limited to a comparatively few instances.

CHAPTER 41B

PIPE LINES*

Construction Practices, Arc Welding of Pipe Lines, Roll Weld Method, Stove Pipe Method, River Crossings, Testing, Types of Pipe Joints, Oil, Gas and Gasoline Lines, Specifications, Bell-Hole Welding, Workmanship, Equipment, Gas Welding, Joint Design, Pipe Welding Technique, Procedure, Pipe Cutting, Welding Organization.

1. INTRODUCTION AND EXTENT OF APPLICATION

Fusion welding has been used so long with such completely satisfactory results that for years it has become the accepted standard method of construction of pipe lines for cross country transportation. This country is literally criss-crossed with welded overland lines some of which extend over a thousand miles in length. These pipe lines vary, of course, as to size and materials used. The usual sizes employed and welded for this purpose are: all sizes up to 16 in. O.D. for oil transportation lines, up to 16 in. O.D. for gasoline transportation, up to 26 in. O.D. for gas, and up to 120 in. O.D. for water. As to material used, practically all steel pipe purchased under A.P.I. or A.S.T.M. specification is suited for welding. The only limitation is that the carbon content shall not exceed 0.35%. If higher carbon or special alloy steel pipe is used, special precautions and procedures must be applied depending upon the material used.

This chapter is limited to description of arc and oxyacetylene field welding of steel pipe for transportation purposes.

2. GENERAL PIPE LINE CONSTRUCTION PRACTICES

In the construction of welded pipe lines certain collateral operations are commonly involved whether the welding is performed by the electric arc or the oxyacetylene methods. The quality of the finished line and the speed with which it is installed are directly influenced by these operations,

*Prepared by a committee consisting of H. C. Price, H. C. Price Co., *Chairman;* T. W. Greene, The Linde Air Products Co.; and A. N. Kugler, Air Reduction Sales Co.

hence proper control and coordination of them is of vital importance to the successful completion of a welded pipe-line project.

The preliminary preparations for pipe-line construction follow the general pattern for all engineering work. Thus surveys of the proposed routes of the line are made. These surveys may be made by the conventional transit line methods or the newer aerial techniques. Following this the necessary plans are prepared together with specifications. These specifications will encompass all phases of the work, equipment, material and testing and must cover the detailed requirements for welding, including welding operator qualifications. Under material it is wise to be specific on the type of steel pipe to be employed to insure weldable quality steel.

With the route of the line established by the surveys and the right-of-way secured, the next step is that of clearing the right-of-way of trees and obstructions so that construction operations may be carried forward. Following this the ditch for the pipe is dug, for which it is almost universal practice now to employ ditching machines. The next operation, that of stringing the pipe along the right-of-way may occur at this stage or may precede the ditching operations. Trucks are employed for moving the pipe from the railroad cars to conveniently located distribution points along the line. Tractors equipped with booms generally spot the individual lengths of pipe along the ditch. It should be noted that all of these operations are preliminary to actual welding which up to this point has not been employed.

The organization of the crews for actual welding depends to a large extent upon the method of laying the pipe as well as the welding procedure, i.e. whether the "all-welded," "stove-pipe" or "composite" construction methods are employed and whether oxyacetylene or arc welding is utilized. Since detailed labor requirements for each of these will be found under the appropriate headings only brief outlines are included here.

All-Welded Method

All-welded construction, as the name implies, means that the line is completely welded throughout. For installing pipe by this procedure the following organization is generally employed:

(*a*) Line-up gang
(*b*) Firing-line gang
(*c*) Tie-in gang
(*d*) Lowering gang*
(*e*) Bell-hole gang*
(*f*) Backfilling gang

The function of the line-up gang is to line up the pipe on skids or dollies adjacent to or over the trench. Clamps which hold the pipe ends in alignment are used while tackers in the gang make the required number of tack welds. Obviously these tack welders do not require the same degree of skill necessary for the other welding. In these lining-up operations it is common practice to tack weld from two to five lengths of pipe into a so-called "string" in preparation for the firing-line gang. The exact number of lengths in a string is largely dictated by the terrain, job conditions and the availability of equipment.

* In present-day practice, these two gangs are consolidated.

The firing-line gang performs the actual welds on these strings of pipe employing one of several generally acceptable procedures. Operators may be stationed at each weld in a string, each making complete welds while a helper turns the pipe. One operator may make all welds in a string while the helper turns the pipe. This method is more commonly used in arc welding, in which case a second helper cleans the weld after each pass. For firing-line operations the operators are only required to weld in the flat position since the pipe is rotated during welding. Consequently the progress of the firing-line gang is quite rapid. The equipment for this crew is governed by its size and whether arc or gas welding is used.

At this stage in the construction the line consists of a series of strings of welded pipes ranging from 80 ft. to 200 ft. (40-ft. lengths assumed) depending on the number of lengths used per string. Each string is supported over or adjacent to the trench. The next step is that of tying these strings together. Since long lengths are now involved the pipe cannot be rotated and, therefore, position welds must be made. The operator, in making these tie-in welds is, therefore, called upon to weld in the flat, vertical and overhead positions. This requires a high degree of skill and only competent operators should be permitted to do this work. Fortunately these position welds constitute but a small portion of the total number of welds.

In the older construction procedure these long strings of pipe, usually 1000 ft. or more in length, next received a protective coating to retard corrosion, following which they were lowered into the trench which was then backfilled. Care had to be exercised in this operation to insure the absence of torsional and tension strains in the pipe. To avoid the former, the tendency to twisting was controlled when lowering the pipe. The latter condition was minimized by lowering and backfilling the line during a period of relatively low temperature, generally early in the morning.

At this stage the line is covered in the trench, except at those points where it is necessary to join these long strings of pipe together. In order to permit the operator to make these difficult position welds with the pipe underground, it is necessary to widen the ditch. The resulting hole is somewhat in the shape of a bell, hence the name "bell-hole weld." Obviously only the most highly skilled welding operators are permitted to weld these joints. With the completion of the "bell-hole" welds the line is virtually completed except for backfilling these holes.

The newer method of construction consolidates the operation of "bell-hole" welding the 1000 ft. long strings with the operation of backfilling. Thus a tie-in operator is assigned to the lowering gang and he makes the welds, tying these long strings, usually above ground. When the joint has cooled sufficiently the protective coating is applied and the line lowered and backfilled, leaving just enough pipe exposed to make the next tie-in weld. This phase of the procedure, therefore, is somewhat analogous to "stove-piping" which will be described later. Aside from the reduction in organization which this method makes possible, it has the added advantage of lessening the tendencies to torsional and tension strains mentioned earlier.

The finished pipe line, buried in the ground, must be connected to the pump or compressor stations located at convenient intervals. The installation of the large amounts of piping at these stations is handled by other

crews since the work is of a different nature. Crossings, under-roads and railroad rights-of-way involve special construction, hence they are generally built by crews specially equipped for this work. Similarly, when it is necessary to cross rivers and streams the common practice is to use extra heavy pipe and heavy clamps over the welded joints to insure that the line will stay at the bottom of the stream. In some instances the main line is broken down into several smaller lines, by means of headers, for crossing rivers, etc. Again this work is performed by special crews.

Stove-Piping

Under the stove-pipe method of construction each joint is handled individually and welded onto the line, one joint at a time. The lining up of pipe in long sections and the roll welding are eliminated. Stove-pipe method is particularly applicable in extremely rough or muddy country. It is also more economical on small diameter lines, that is, 6 in. or less, in good or bad country. In extremely rough or muddy country only a limited amount of pipe can be laid per day by any method, because of the difficulty in transporting equipment. With this limited progress in construction, only a comparatively small number of welds are daily required. It is found that, even though all of the welds are position welds, the same progress can be made by the addition of one or two welding machines, and at the same time eliminating the line-up crew and their tractors. (For detailed procedures see sections on arc and gas welding.)

Composite Construction

Composite construction, as the name indicates, is a combination of welded construction with some form of mechanically coupled joints. It is used in some instances on large diameter gas lines where the difficulty in securing proper expansion and contraction provisions in a solid welded line make the mechanical connections desirable. Further, the use of couplings, usually of the friction or pressure types, eliminates all position welds.

In practice this method employs similar procedures to those noted for the first process. Strings of three or four lengths are roll welded along the right-of-way by firing-line gangs. Following this the strings are placed on skids over the trench and the couplings applied to the ends. Then a bolting gang makes up the coupling. The line is then given the protective coating and lowered and backfilled. It will be observed that the size of the organization for this method is between that for the all-weld procedure and that for stove-piping. As in the previously discussed procedures, river and road crossings and special features are handled by gangs equipped for this work.

Testing of welded lines is an important phase of the work and if properly carried out will go a long way toward insuring a sound line and freedom from breakdowns in service. Since methods of testing are substantially the same for all three of the foregoing procedures, a general discussion will be adequate. The first step is that of qualifying the operators who will weld on the lines. In this it is customary to require the candidates to make test welds simulating actual job conditions. Thus a firing-line welder is tested by having him make a rolling weld whereas tie-in and bell-hole op-

erators are required to make horizontal pipe position welds. Test specimens are removed from these welded samples and tested in tension in portable, hydraulic tensile testing machines. Bend tests, particularly those which place the root or bottom of the weld in tension, are also used. The tension specimens must break outside the weld, or if in the weld, at the minimum strength specified for the pipe material. Bend test specimens must bend 180°, i.e., substantially flat, around a radius equal to twice the thickness of the specimen. Under this test, no cracks greater than $^1/_8$ in. in any dimension should appear.

In the testing of a finished line, destructive tests such as used in qualifying operators, are not suitable for obvious reasons. If, however, a given weld is questioned it is a wise precaution to remove it in its entirety and test as for a qualification. The gap thus left in the line is repaired by welding a short section usually called a "dutchman." Pressure tests, either air or hydrostatic, are used to determine the tightness of a line. The former is more commonly used since an air compressor is almost universally available. Hydrostatic tests on long lines are uneconomical as well as difficult to perform.

In making pressure tests with compressed air, it is common practice to test strings before lowering and backfilling. A pressure of 100 psi. is commonly used and temporary, removable caps held by pressure type couplings are used to close the ends. Under test a line must hold the pressure for a specified length of time; adjustments are made for temperature variations during the test. If a pressure drop is noted then the section is examined for leaks. Minor leaks are repaired by chipping or flame gouging the affected area and rewelding, exercising due precautions to insure freedom from locked-up stress. Major leakage in a joint calls for complete removal and rewelding.

Longer sections of the line, between convenient shut-off points such as valves, are tested similarly. In some cases, particularly where short sections have been tested with air, the final test of the line is made under actual working conditions, i.e., the line carrying the gas, oil or gasoline at the normal working pressure.

A study of this brief résumé of pipe-line construction practices brings out the fact that close coordination of all units of the organization is of the utmost importance to efficient economical operations. Obviously a failure in even one relatively insignificant unit of the organization can cause virtually complete stoppage of work. Yet when properly organized and operated welded pipe lines are installed at such rapid speeds as to approach the unbelievable.

3. ARC WELDING OF PIPE LINES

Roll Weld and Tie-In Method for Solid Welded Lines

Operation in pipe-line welding today is a straight line procedure. Under the above method it is divided into three operations:

A—Lining up and tacking.
B—Roll welding into long sections.
C—Tie-in welding of the long sections in or over the ditch.

A. Line-up.—After the pipe is strung along the right of way it is first swabbed to clean out any accumulation of foreign material. Immediately

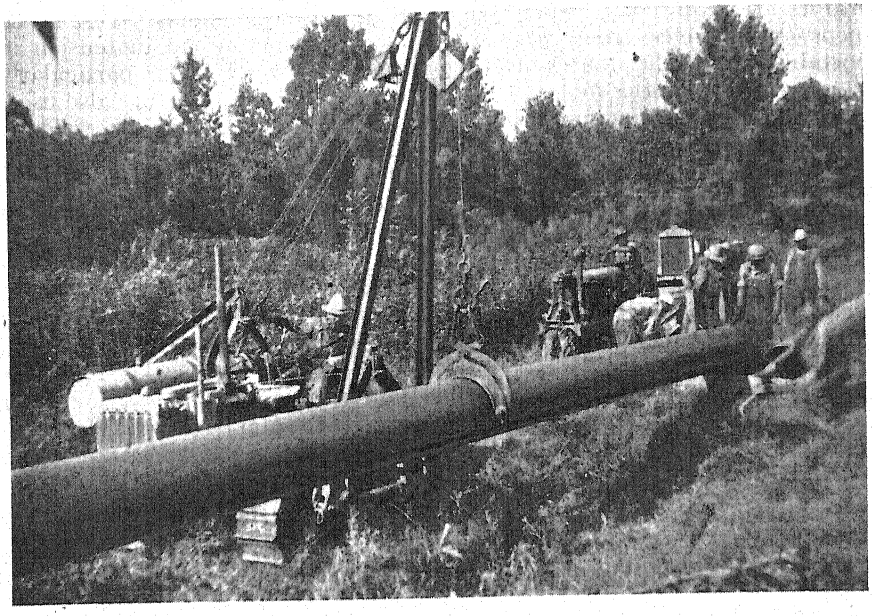


Fig. 1—Line-Up Crew. Showing Tractor Lifting Pipe Joint Onto Skid

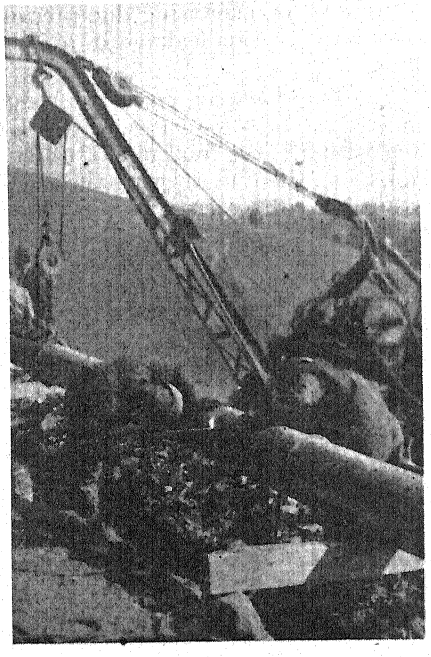


Fig. 2—Operator Tacking Pipe as Lined Up

after the swabbing the pipe bevels are cleaned, if necessary, of any rust, grease or paint. The pipe is then lined up by the line-up gang (Fig. 1). The number of pipe lengths in each section varies, according to the nature of the terrain. The average section is 200 ft. in length.

An operator with the line-up gang tack welds the joints together as they are lined up, putting on three or four equi-distant tacks (Fig. 2). The sections of pipe are lined up on rollers or dollies, placed on skids, so that the pipe can be rotated beneath the arc when welding the joints. A line-up clamp (Fig. 3) is used when lining up plain end joints.



Fig. 3—Line-Up Clamp Used in Lining Up Plain End Pipe Without Backing Up Ring

B. Roll Welding.—Following the line-up crew come the roll operators, known as the firing line (Fig. 4). Only one operator is used on each long section. This welder applies the first bead completely around the pipe. Welding from the top, he holds the puddle on the top of the pipe and welds toward himself as the pipe is turned in the opposite direction. Upon the completion of the first bead on one joint, the welder will proceed to make the first beads on the remaining joints of the section. While he is doing this his helper, using brush and chisel, will clean the beads already made. Upon completion of the first beads the welder will then proceed to put a second bead on each joint under the same procedure, and continue in the same manner with as many additional beads as are necessary or specified. Where a backing-up ring is used inside of the pipe, only two beads are usually necessary. Where no backing-up ring is used three or more beads are necessary, depending upon the thickness of the pipe.

C. Tie-in Welds.—After a section of the line is completely welded, it is rolled off the dollies adjacent to the ditch. The dollies and skids are then moved ahead to be used on other sections. The pipe crew then places the

long sections on skids over the ditch, lining them up for the tie-in welder. When the long sections are accurately lined up they are tacked together in the same manner as are the individual joints. However, if a bend is to be made in the section, the tack welder completes the first bead. The bend is then made by the pipe-laying crew. The tie-in welders then proceed to weld the long sections together into a completed pipe line (Fig. 5). As it is evident that the completed pipe line cannot be rolled, it is necessary that each tie-in weld be a position weld, that is, the weld is made by moving the arc around the pipe. A small electrode of no greater diameter than $^{3}/_{16}$ in. being used for this type of weld, it is necessary to apply at least three beads on all tie-in welds. Each bead is thoroughly cleaned before the application of the succeeding bead. Although the pipe is usually on skids above the ditch, it is necessary that the sides of the ditch be shoveled down or bell holes dug in order to give the welding operator sufficient space to proceed completely around the joint. After the tie-in welds are completed the pipe is then ready to be lowered into the ditch.

Fig. 4—Roll Welder and Pipe Turner

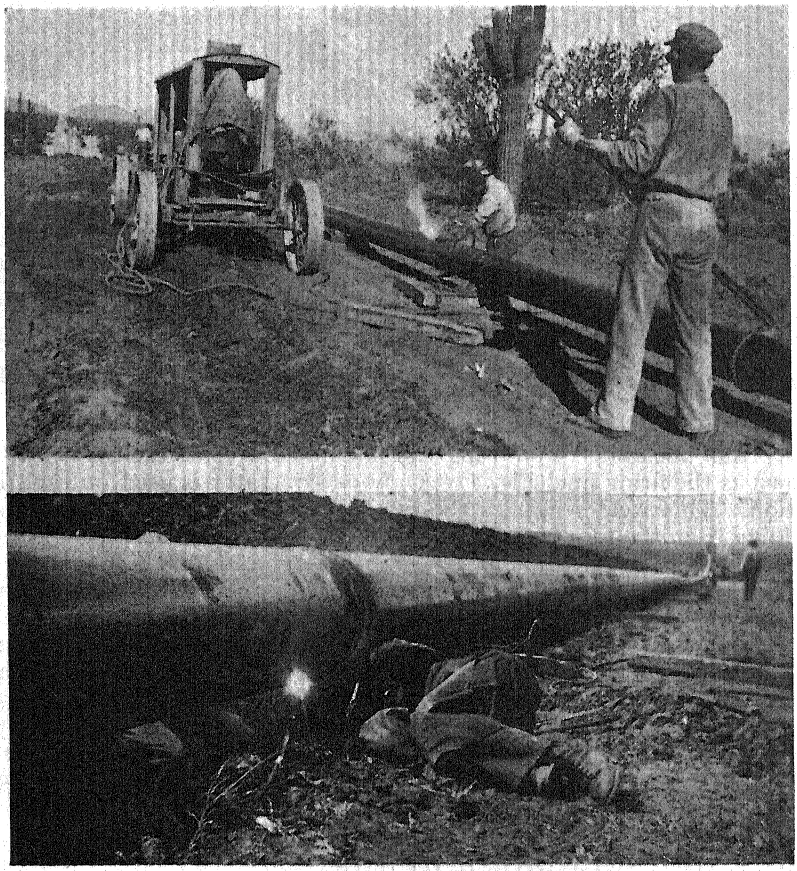


Fig. 5—Welder Making Tie-In Weld

Roll Weld Method for Combination Welded and Coupled Lines

At the present time nearly all of the oil and gas pipe lines, regardless of diameter, are solid welded. However, for reasons of contraction and expansion, some large diameter gas lines, that is from 16 in. up, are being constructed with the use of a coupling every 80 ft. or 120 ft. On such lines

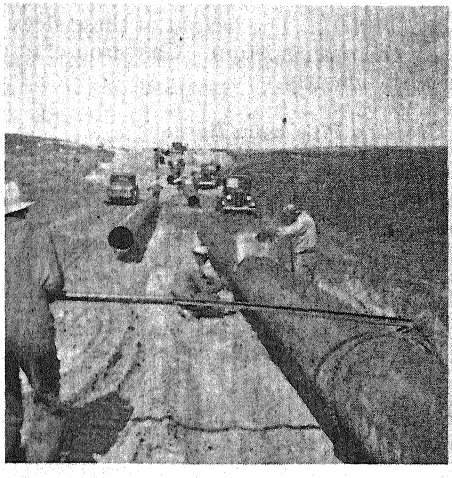


Fig. 6—Roll Welding 80 Ft.-Sections of Composite Welded and Coupled Line

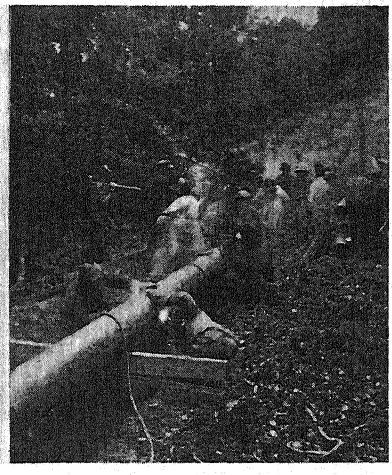


Fig. 7—Two Welders Making Tack and First Bead (Stove-Pipe Method)

it is self-evident that the tie-in welds are eliminated. The pipe is lined up and roll welded in short sections of two or three joints (Fig. 6), as above described.

Stove-Pipe Method

Stove-pipe welding is performed under the following procedure:

The right of way is cleared, pipe strung, and the ditch dug ahead of the welding operations. Each joint is lined up on skids across the ditch, and as a subsequent length is laid over the skids two welders immediately tack same and apply the first bead completely around the pipe (Fig. 7). The welders work on opposite sides of the pipe. Following the tackers come the main welding gang. These welders complete each weld by adding a sufficient number of additional beads by the usual tie-in method.

Bending of the pipe is done either on single lengths before they are placed over the ditch and tacked, or after the first bead is welded.

River Crossings

River crossings are always solid welded throughout. The pipe is usually roll welded in long sections of 200 ft. or more. If the river is of comparatively narrow width, the long sections are welded together on the bank

and the entire line pulled across the river in one section, after which it is tied into the main line on the banks. On very wide rivers the welding is done from a barge on the river (Fig. 8). The pipe is usually welded into 80-ft. sections before it is placed on the barge. It is then lowered into the river, one section at a time, the section on the barge being welded to the section that is partially in the water. Extra heavy pipe, often of a thickness of $^1/_2$ in. or more, is used. For added protection, heavy split sleeves are sometimes welded over the pipe joints (Fig. 9). The weight of these sleeves also helps in keeping the pipe down on the river bottom. Cast-iron clamps are sometimes used to weight the pipe sufficiently.

Fig. 8—Laying River Crossing Pipe from Barge



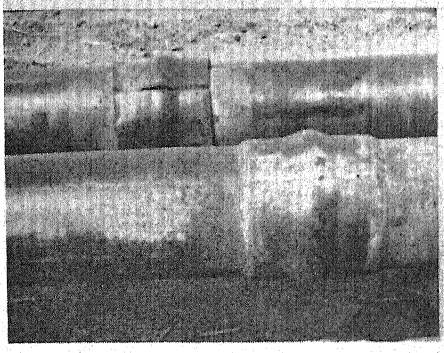


Fig. 9—Reinforcing Sleeves Welded on River Crossing Pipe

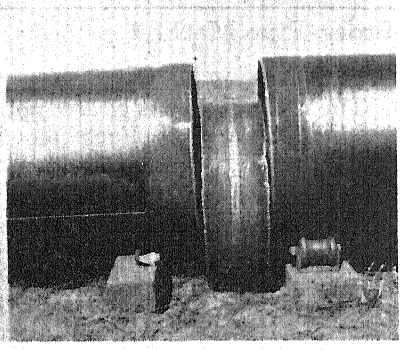


Fig. 10—Welded Section Cut from Pipe Preparatory to Testing

Testing

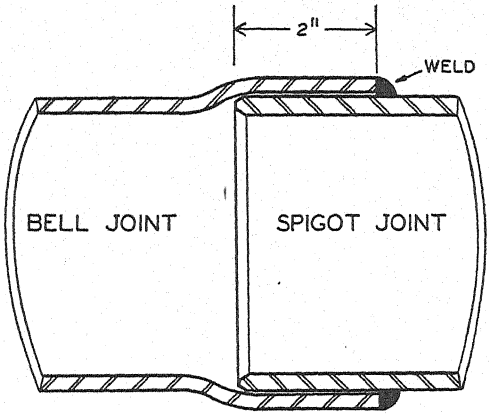
(*A*) *For Tensile Strength and Ductility.*—A complete weld is cut out from the pipe line, cutting the pipe 4 in. back on each side of the weld. After the

8-in. section is taken out of the line (Fig. 10), a specified number of coupons, usually four, each of which is 1 in. in width, are cut across the weld parallel to the axis of the pipe. These coupons are cut equi-distant from each other. They are then placed in a portable pulling machine and tested for tensile strength, as noted later. If a bend test is also specified, additional coupons are cut from the same 8-in. section of the pipe. This method of testing applies to all methods of welding.

(*B*) *For Leakage.*—Most oil lines are tested for leakage after the line is completed, by bringing up the oil pressure to the ultimate working pressure and shutting it in for 24 hours. Any appreciable leakage will result in a drop of the pressure. On some gasoline or gas projects the line is tested at the end of each day's work with 100 lb. air pressure. Heavily soaped water is brushed completely around each weld to detect any leaks.

Types of Pipe Joints for Arc Welding

Bell and Spigot Joint.—The first type of joint used for connecting pipe by arc welding was the bell and spigot (Fig. 11). As shown in the sketch, to make this joint one end of the pipe was belled out, while the other one was of such diameter as to fit neatly into the belled end. The belling of the pipe end was for a distance of approximately 2 in. from the end of the pipe.



BELL AND SPIGOT JOINT
Fig. 11

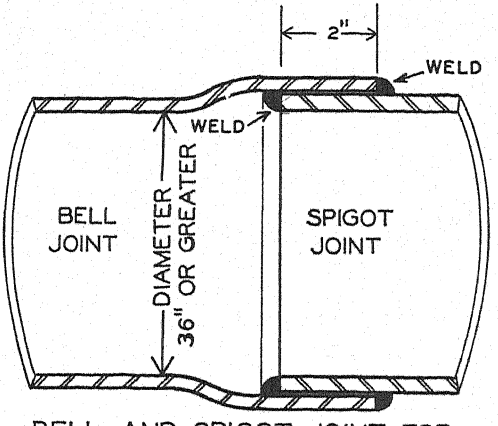
In making this joint, the spigot end of one pipe was placed in the bell end of the connecting pipe, then a fillet weld was made completely around the joint. Although the bell and spigot joint has been replaced with a more efficient joint for construction of oil and gas lines, it is still used, because of convenience in construction, for connecting large diameter water pipes

Bell and Spigot Joints for Water Lines.—As water lines of 36 in. diamete or greater, are welded both inside and out, it is necessary that both the end of the bell and the spigot pipe be square cut (Fig. 12).

Double-Bell Joint with Backing-Up Ring.—As shown in the sketch in Fig. 13, the double-belled joint with backing-up ring requires that the ends of

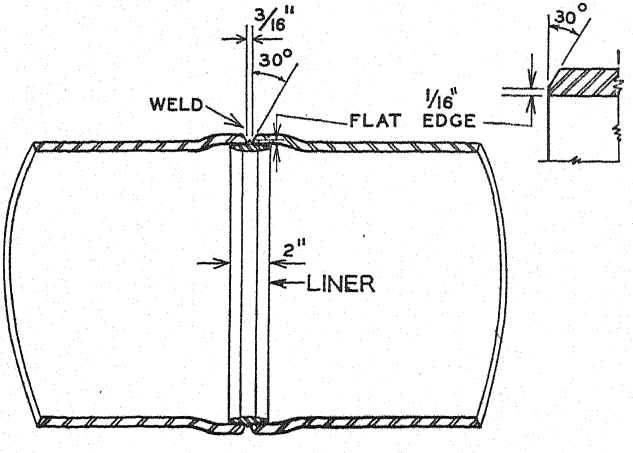
both connecting pipes be belled, and also that a backing-up ring 2 in. to 6 in. in width be placed inside the pipe. This ring is made with an annular raised ridge so that when placed in position it allows a space of $^3/_{16}$ in. between the belled ends of the pipe. For this type of joint, the end of each pipe is usually beveled to 30°, leaving a vee totaling 60° for application of the welding beads.

Butt Joint with Backing-Up Ring.—The joint shown in Fig. 14 is used in the construction of gas pipe lines of 10 in. or more in diameter. The ring inside of the pipe for gas lines provides only negligible resistance to flow. Therefore, this type of joint can be used in gas line construction, whereas it cannot be used in pipe lines handling liquids. As shown in the sketch,



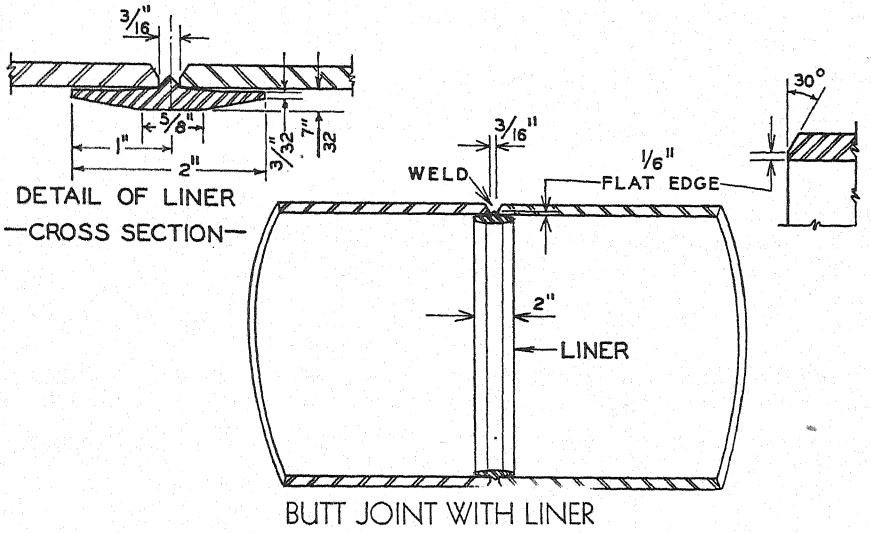
BELL AND SPIGOT JOINT FOR LARGE DIAMETER WATER LINE

Fig. 12



DOUBLE BELL JOINT WITH LINER

Fig. 13

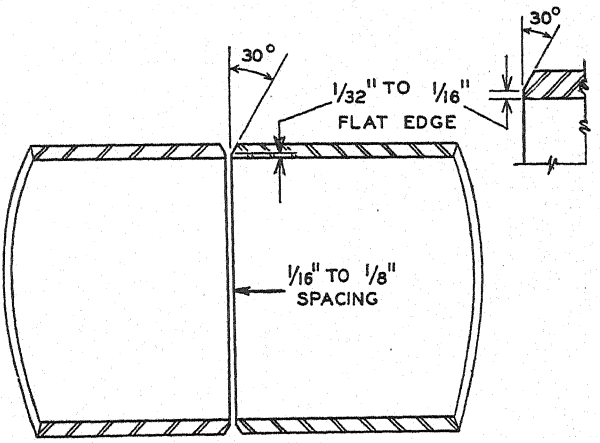


BUTT JOINT WITH LINER

Fig. 14

this type of joint is similar to the double-bell joint in all respects, except that the pipe ends are straight instead of belled.

Butt Joint.—For this type of joint shown in Fig. 15 the pipe is straight as it comes from the mill, without the use of any bell or backing-up ring. The ends of the pipe are beveled at an angle of 30° with the vertical making an included angle of 60°. The vertical shoulders at the bottom of the bevel of all butt joints, whether used with a backing-up ring or not, should not be greater than $^1/_{16}$ in. For butt joint, without a backing-up ring, $^1/_{32}$-in. shoulder is preferred.



BUTT JOINT WITH OUT LINER

Fig. 15

Comparative Quality and Costs of Pipe Joints with and Without Backing-Up Ring

There is considerable difference of opinion as to the efficiency of these two joints. From observation of several thousands of miles of pipe line, no definite difference has been seen in the results obtained from either type of joint after the lines were in operation. It costs less to weld with a backing-up ring for the reason that only two beads are necessary, whereas at least three beads are necessary without a ring. However, on a liquid line the cost of double-belling the pipe more than offsets this saving. On gas lines where double-belling is unnecessary, the saving in the cost of welding offsets the cost of the ring. The welding operator can use a large rod and high current on the first bead with no danger of burning through the ring. When no ring is used, the first bead must be applied carefully to assure thorough penetration without burning a hole through the pipe. Only the best welders should be used in making the first bead on pipe joints without a ring, as the quality of the weld depends upon the quality of the first bead.

Specific Methods of Operation and Types of Joints as Applicable to Oil, Gas or Gasoline Lines

Oil Lines.—Practically all oil lines are welded without the use of a backing-up ring. If a backing-up ring is specified, it is also necessary to specify double-bell pipe. A backing-up ring could not be used in butt joints on an oil line for two reasons: first, it would restrict the flow of the fluid and, second, it would be impossible to get a "go-devil" cleaning device through the pipe line after completion.

Gasoline Lines.—Both plain end without ring, and double-belled pipe with ring are used on gasoline line construction. It is absolutely necessary that the pipe on gasoline lines be thoroughly clean internally at all times. By using the double-bell pipe with ring, no particles of metal can fall inside of the pipe line during welding. It is for this reason that this type of joint is specified on some gasoline lines. However, during the past two years it has been rarely used.

Pipe for use on gasoline lines is often shipped from the mills with thin metal covers, spot welded over the ends. This is done to prevent any foreign matter or dirt from entering the pipe. These covers are not removed from the pipe ends until immediately before the pipe is lined up for tacking. They are also left on the ends of the long sections until these sections are placed over the ditch and ready for the tie-in welds. When the covers are used it is not necessary to swab the pipe. A gasoline line, using these covers, proves to be exceptionally clean when placed in operation.

Gas Lines.—There has been a decided trend in the past two years toward the elimination of the use of backing-up rings in gas lines regardless of the diameter of the pipe. Gas lines with diameter up to 26 in. are now being universally welded using a butt joint without backing-up ring.

Suggested Specifications for Pipe-Line Field Joints with Backing-Up Ring

Cleaning Pipe Before Welding.—Any suitable means approved by the Company for whom the pipe is furnished may be used for thoroughly clean-

ing the ends of the pipe before the actual welding or tacking operation. All paint, rust, scale, dirt or other foreign matter that might affect the welding operation shall be removed prior to welding. It is understood that the pipe purchase orders will specify that the pipe is not to be primed or greased within 6 in. of each end.

Welding Rod.—The Contractor shall furnish and use heavily coated electrode giving a "shielded arc." (A.W.S.-A.S.T.M. Tentative Specifications for Iron and Steel Arc-Welding Electrodes, Serial Designation A 233–42T.) The Company reserves the right to reject any shipment of rod found to be of inferior quality, should this, in their opinion, become necessary to improve the efficiency of the welds. The Contractor shall protect the rod from any deterioration prior to using.

Amperage.—The contractor shall at all times use the proper amount of heat or amperage for the size and kind of rod used.

Tacking.—Each tack weld shall have a thickness of not over two-thirds of the pipe wall. Tack welds are to be free from pinholes so that the completed weld will have 100% of the pipe strength at the points of tacking. All tacks are to be cleaned free of scale and oxides before making the welds. Only sufficient tacks shall be made so that the alignment of the joints will be retained.

Roll Welding.—All rolling welds shall be made in at least two beads. The welding puddle shall be maintained at the top center of the pipe. The first bead shall be applied completely around the pipe and shall be thoroughly cleaned of all scale, dirt, coatings, slag, etc., prior to the application of the second bead. The method of cleaning the welds shall be approved by the Inspector. Wire brushing alone may not suffice. The completed weld shall be free from pinholes, non-metallic inclusions, air pockets or any other defects. The completed weld shall have a reinforcement above the wall thickness of the pipe at all points averaging $^1/_{16}$ in. An additional bead or a portion thereof, whichever is necessary, is to be put on where the Inspector determines this procedure necessary due to a lack of reinforcement. The completed weld is to be cleaned free of scale and oxides.

Bell-Hole or Tie-In Welding.—Three beads or more shall be used in making tie-in welds. Each bead shall be cleaned of all scale, slag, dirt, etc., prior to the application of each succeeding bead. The dimensions of the completed weld shall be the same as for rolling welds. The point of starting shall be acceptable to the field Inspector. Tie-in welds are to be free from pinholes, non-metallic inclusions, etc.

Weld Characteristics.—The intent and purpose of these specifications is to make possible a 100% weld as to strength, ductility, fusion and penetration for the entire circumference of the weld, including the points at which the tacks occur.

The tensile strength of the weld shall not be less than the minimum tensile strength guaranteed on the pipe. This minimum tensile strength shall be determined in the field with a portable tensile testing machine.

The ductility or penetration of the weld shall be such that coupons cut from the weld in the field will withstand a bend test of at least 90° in either direction without fracture. The coupons used for bending will have the reinforcement removed so that the coupon will have the same thickness

throughout its entire length; also a notch will be ground or cut into both edges of the weld so that the bend will be completely on the weld.

In conducting these bend tests, the specimens will be placed in a bending apparatus and bent around a pin $^1/_2$ in. in diameter. The penetration shall not be less than the original thickness of the pipe wall.

Competent Workmen. The Contractor shall use only competent and skilled workmen for welding and all work shall be completed in a workmanlike manner to the satisfaction of the Inspector. Should any operator perform work which is not satisfactory to the Inspector, such workman will be immediately released by the Contractor. Before being allowed to weld on the line, each operator is to pass a satisfactory welding test to insure the Inspector that he is competent.

Testing and Stenciling of Welds.—The Inspector shall stencil each weld with the operator's number for the purpose of future identification. Girth welds will be cut out of the line under the direction of the Company's inspector from which coupons shall be cut for tensile or bending tests. As many coupons shall be cut from any weld as are deemed necessary, but they shall be cut at equal distances around the circumference. The cutting and rewelding of any welds found to be defective shall be done at the expense of the Contractor. The cutting and rewelding of welds which have proved satisfactory upon test shall be paid for by the Company at a stipulated price. The Company reserves the right to select welds whenever the occasion demands for the purpose of testing.

General Arc-Welding Clauses.—The welding Contractor is to furnish a suitable number of dollies for rolling the pipe, the normal length being in five-joint sections. In case of windy weather suitable wind guards shall be provided for protection of the work. Welding shall not be carried on when, in the judgment of the Company inspector, the weather is unfit. If any pipe shall be improperly welded, the defective portion should be cut out and the joint rewelded, the expense of which shall be borne by the Contractor. All welding equipment shall be maintained in first-class condition and shall be subject to the approval or rejection of the Company at all times. The use of mitered welds will not be permitted.

The pipe ends shall be beveled at an angle of 30° with the vertical making the included angle 60°. This angle will be subject to change, if necessary, to improve the welding.

Any beveling done with a cutting blow torch must be properly cleaned and all oxide formation removed by hammer and chisel, file, brush or other suitable method. Should laminations or split ends develop in the pipe during the process of welding, the full joints containing these said defects shall be removed from the line and they are not to be used later in the main line construction, and the removal of defective joints shall be done at no added expense to the Company.

On the initial bead the maximum size rod for the minimum spacing shall be used at all times.

Suggested Specifications for Pipe Line Field Joints Without Backing-Up Ring

These specifications are identical to the above, with the following exceptions:

Roll Welding.—All roll welds should be made in at least three beads. Each bead shall be applied completely around the pipe and shall be thoroughly cleaned of all scale, dirt, coatings, slag, etc., prior to the application of the subsequent bead.

Equipment

The following is the equipment usually necessary for a complete organization using the roll weld and tie-in method:

Line-up Crew. Large tractor, with live boom, used to pick the pipe off the ground and place same on dollies.

Line-up clamps.

300-Ampere gasoline-driven welding machine for tacking.

Roller bearing dollies for large pipe—that is, 16 in. or more.

Plain dollies for smaller pipe.

Roll Welding Crew. 400-Ampere gasoline-driven welding machines where $^5/_{16}$-in. or $^3/_8$-in. rod is used.

300-Ampere gasoline-driven welding machines where $^1/_4$-in. rod or smaller is used.

Tractors or trucks to move machines, depending on the terrain.

Tie-in Crew. 200-Ampere gasoline-driven machines.

Tractors or trucks for moving equipment, depending on terrain.

All of the data included in the following tables are based on the use of the heavily coated or shielded arc electrode:

Table 1—Average Speeds of Pipe Line Welding

(The following data are not the actual time consumed in making each individual weld, but are the average time consumed in making all welds on an average length pipe line from start to finish of the job, and include delays, breakdowns and moving time. In other words, they are the average production that can be expected per welder per hour on pipe-line construction.)

Size Pipe, In.	Average Welds per Hour		
	Roll Welding Without Backing-Up Ring (Three Beads)	Roll Welding with Backing-Up Ring (Two Beads)	Position Welding (Stove-Pipe Method)*
6	6.0	7.0	5.0
8	5.5	6.5	4.0
10	4.0	5.0	3.0
12	3.0	4.5	2.0
14	2.75	4.0	
16	2.5	3.5	
18	2.4	3.25	
20	2.25	3.2	
22	2.1	3.1	
24	2.0	3.0	
26	1.8	2.5	

* Without Backing-Up Ring After First Bead Run by Tackers.

Table 2—Spacing of Pipe Joint for Welding

Roll and Position Welding Without Backing-Up Ring For All Sizes of Pipe Use a Space Of from 0.040 in. to 0.065 in.
Roll and Position Welding With Backing-Up Ring For All Sizes of Pipe Use a Space of from $^1/_8$ in. to $^3/_{16}$ in.

4. GAS WELDING OF PIPE LINES

Although the first long welded line (80 miles in length) was oxyacetylene welded in 1918, it was three to four years later before welding was extensively accepted.

The construction of welded pipe lines is a production welding operation in which the factor of organization is particularly important. Welding must be properly coordinated with the other operations so that the work can progress steadily. Speed is usually a factor in the construction of the line, so that the welding method must be capable of producing welded joints at a high rate. At the same time the welds must be of superior quality due to the high operating pressures encountered in oil and gas transmission lines.

To keep pace with the demands of the pipe-line industry, welding techniques have been constantly improved and organization methods perfected. Other oxyacetylene applications which are widely used by the industry include: wrinkle bending, in which the oxyacetylene flame is used to heat the pipe for bending; and oxyacetylene cutting, which is used for beveling pipe ends for welding and pipe fabrication in general.

Joint Design

The open butt joint is the standard line joint and is recommended for all pipe-line services and pressures. The theoretical strength of this pipe joint requires no discussion since the deposited weld metal merely replaces a portion of the pipe wall cut away, becoming an integral part of the pipe itself. It is this fact that is mainly responsible for the simplicity of joining pipe with the butt type weld.

The symmetrical shape of the butt type joint makes it by far the easiest to oxyacetylene weld. The ends of the pipe form a natural trough for the welding puddle as it is carried along in producing the weld, and the gap permits complete fusion of the weld at the bottom of the joint. The molten weld metal at the front of the puddle is comparatively viscous and will span a gap of $1/8$ in. and more without sagging inside of the pipe. In this way the bottom of the vee is completely welded right down to the inside wall without protrusions.

Where the wall thickness of the pipe is $3/16$ in. or over, the ends of the pipe are beveled to within $1/16$ in. of the inside wall of the pipe. The angle of bevel varies from 25° to 45°, depending upon the welding technique to be used. When the beveled ends are brought together they form a trough or vee having an included angle of 50° to 90°.

In this joint design provision is made for a gap or spacing between the pipe ends. This should be between $1/16$ and $1/8$ in. during the welding operation. A spacing of $1/16$ in. greater than the above amounts is allowed before tack welding. This spacing facilitates thorough fusion of the weld metal with the pipe metal at the bottom of the vee.

Pipe-Welding Technique

There are two basic techniques for oxyacetylene welding steel pipe—forehand and backhand.

With forehand technique, the welding rod precedes the blowpipe or torch tip in the direction in which the weld is being made and the flame points ahead—away from the completed portion of the weld.

With backhand technique, the blowpipe or torch tip precedes the rod in the direction of travel and the flame points back at the molten puddle and completed portion of the weld.

The forehand technique is usually used with a neutral flame, while an excess acetylene flame is generally used with backhand technique.

The combination of backhand technique, excess acetylene flame and welding rod of suitable composition is widely used in pipe-line welding. It gives welding speeds from two to four times faster than former oxyacetylene methods. It reduces consumption of welding gases and rod by as much as 25%. It makes full strength welds capable of resisting any pull, bending or shock the pipe must withstand—welds that remain leakproof permanently.

The introduction of multi-flame heads or tips has still further increased the speed and economy of pipe welding by the oxyacetylene process. Multiflame welding gives an increase in welding speed of about 33% over single flame welding as well as a 15 to 25% saving in gases and rod while maintaining the same high standard of weld quality.

Advantages of Backhand Technique

An advantage of backhand technique, particularly in rotation (roll) weld ing, is that the manipulation is simpler and quicker, for the flame and rod can be moved in the same or opposite direction, as desired, instead of in a circular or elliptical motion. Thus the hottest portion of the flame is directed almost constantly against the end of the welding rod increasing the rate at which the welding rod melts. Furthermore, the operator is in a better position to observe the progress of the molten puddle and to move it along just as fast as the sides and bottom of the vee are ready for it. Contraction of the spacing ahead of the weld is also less with this techniquet which makes possible a narrower vee and hence a reduction in the amount of welding rod required.

Effect of Excess Acetylene Flame.—The excess acetylene flame has a beneficial effect on the base metal surface just ahead of the advancing puddle. (See chapter on Fundamentals of Gas Welding.) The carburizing effect of the flame tends to prepare and reduce the melting point of the surface so that perfect fusion of the base metal with the molten metal from the welding rod takes place without deep melting of the base metal. There is thus an increase in the efficiency of welding and in the uniformity and quality of weld metal. The carbon absorbed in the surface metal also reduces ordinary surface oxide to a form of steel which unites with the puddle. This enables molten weld metal to flow ahead readily over the melting surface of the base metal, making for increased ease in welding.

The torch or blowpipe flame should be adjusted so that the excess acetylene "feather" is between $1^1/_8$ and $1^1/_2$ times the length of the inner cone.

Multilayer Welding

Pipe wall thicknesses up to $^3/_8$ in. are satisfactorily welded in single layers. Thicknesses greater than $^3/_8$ in. present difficulties which, while not

insurmountable, certainly require greater skill. Therefore, a method of depositing welds on heavy wall pipe has been developed which involves making the weld in layers. The recommended procedure is shown in Fig. 16.

The individual layers may be deposited in complete passes around the pipe or the first two layers may be staggered. The latter method offers economies in time and is to be recommended. The operator starts welding the first layer between tack welds and carries this first step of the first layer 2 in. to 6 in. The lengths of these steps are determined by two factors. First, the length is such that the operator can deposit it conveniently without moving the pipe or his position. Second, the length should be such as to permit the starting point to cool down below any show of color due to heat before starting the first step of the second layer. Thus when the second layer is deposited over the first, the originally deposited metal is reheated through its critical range, refining the grain structure and giving it greater ductility. The first two interlocking layers are carried forward together making the circuit of the pipe in one pass with two layers. On three- and four-layer welds each layer after the first two is made as a complete pass or circuit around the pipe.

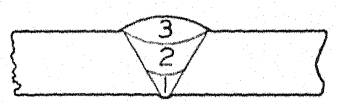
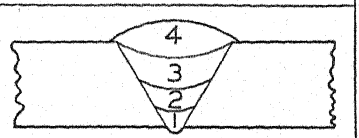
RANGE OF PIPE WALL THICKNESS	NUMBER OF LAYERS	METHOD OF DEPOSITING	CROSS SECTION OF WELD
3/8" TO 5/8"	2	TWO LAYERS ONE PASS	
5/8" TO 7/8"	3	THREE LAYERS TWO PASSES 1 & 2 IN ONE PASS LAYER 3 ONE PASS	
7/8" TO 1 1/8"	4	FOUR LAYERS THREE PASSES 1 & 2 IN ONE PASS LAYERS 3 AND 4 IN TWO PASSES	

Fig. 16—Procedure in Applying Multilayer Gas Welds in Pipe Welding

The advantages of multi-layer welding are twofold. First, it requires less materials and time for heavy walls than single layer welds and consequently is more economical. Second, it produces welds of higher quality. The economies of time and material aremade possible through the simplification in procedure. Since the operator is in effect welding thin sections, welding progresses at a high rate and the extent of puddling is greatly lessened. The improvement in weld quality is also related to the simplification in procedure in that the reduction in puddle size minimizes the opportunities for overheating the metal and entrapping foreign matter. The stress-relieving effect of subsequent layers of weld metal contributes further to improvement in weld quality.

Multi-layer welding can be accomplished by either forehand or back-

hand welding, but the manifold advantages of backhand welding make it the preferred procedure.

Pipe-Welding Procedure

Cleaning.—All scale, rust, dirt or other foreign matter should be thoroughly removed from the joint surfaces before welding. Wire brushing is usually satisfactory for cleaning rusty surfaces. Where joints are prepared by oxyacetylene cutting, the thin, blue-black oxide skin on the cut surface or edge need not be removed. Cutting oxides other than this skin, however, must be entirely cleared away.

Alignment.—The importance of correct alignment of the joints cannot be overemphasized since speed, economy and weld quality are directly influenced by the accuracy with which the joints are spaced and lined up. Pipe clamps, of which there are several satisfactory types on the market, are often useful in obtaining alignment.

Tack Welding.—Following proper alignment, joints should be tack welded so that spacing and alignment can be maintained during the welding operation. Under the best conditions for welding, three tack welds will be sufficient for pipe 6 in. to 14 in. in diameter and four for the larger diameters. Tack welds should be small, about three times the pipe wall thickness in length and two-thirds the pipe wall in thickness of the metal. Each half of the tack weld should slope from the middle to the bottom of the vee, so that the welding puddle can be readily carried over. Tack welds become a part of the final welded joint, so it is important that they be made of the same quality as the final weld.

Making the Weld.—Welds should be started between two tack welds, which helps to preserve proper spacing. Going over tack welds, it is unnecessary to melt them out if they are carefully made. Good fusion between the welding puddle and the tack weld is, however, essential.

If the weld is stopped for any reason, the operator upon re-starting should reheat to a dull red for an overlapping distance of one or more inches, so the face of the weld at the starting point can be brought uniformly to the melting temperature necessary for proper fusion.

To finish a weld, a similar procedure should be followed. Welding should be discontinued approximately $^1/_4$ in. from the finish and the face of the weld at the original starting point, then brought to a melting temperature, first heating to a dull red for one or more inches back. The flame should be directed then to the metal at the point where the welding was stopped and the puddle re-started and carried ahead, just as though going over a tack weld. The puddle should be reduced in size as the full thickness of the weld at the starting point is reached so that it will finally disappear as the flame is thrown gradually ahead.

Rotation (Roll) Welding of Line Joints.—Experience has shown rotation (or roll) welding with backhand technique and using an excess acetylene flame and a welding rod of composition specially suited to be the fastest method of gas-welding pipe joints. The pipe is turned as the weld progresses, the puddle being held within 2 to 4 in. either side of the top center line. The operator may take any convenient position but it is preferred that he stand directly over the pipe because in this position it will not be necessary to bend the welding rod.

The manipulation of the rod and flame is comparatively simple. The inner cone of the flame is first applied at the bottom of the vee until the surfaces sweat or melt slightly, then raised and brought back to bear more on the end of the welding rod and upper portion of the vee, then brought slightly forward and lowered again to prepare the bottom of the vee for the advancing puddle, and so on. The tip of the inner cone should usually be held quite close to but never actually touching the vee, puddle or welding rod. Ordinarily, it will not be necessary to move the flame sideways to prepare both sides of the vee, unless the width of the vee is large compared to the size of the inner cone.

The motion given the end of the welding rod should be a moderate push and pull movement in the line of the joint well within the boundary of the puddle. Some operators have found it advantageous to give the rod a slight rolling motion in the vee; this aids materially in distributing the weld metal. The relative motions of the rod and flame are alternately toward and away from each other. Excessive flames or rod manipulation should be avoided and the metal should not be rippled with the blowpipe or torch or puddled with the rod. The molten metal from the rod should simply be added to the base metal by fusion with the surface, after which overheating or puddling should be avoided.

Overhead Welding of Line Joints.—In making line welds where the pipe is not rotated, the puddle is usually started at the top and carried to the bottom, then re-started at the top and carried to the bottom on the other side. If the pipe is in the ditch it is necessary to dig a bell-hole in which the operator lies while making the overhead part of the weld.

Horizontal Welding of Line Joints.—A modified form of backhand technique is used for this position where the pipe is vertical and the joint is horizontal.

In making the weld the rod is kept in the same relative position as for rotation welding but the flame is pointed slightly ahead and more against the lower side of the vee. Weld metal is built up along the lower side of the vee a little in advance of the upper side, thereby providing a shelf or ledge for supporting the puddle which takes a diagonal direction across the face of the weld.

Wrinkle Bending for Pipe Lines

(*a*) *Wrinkle Bending for Pipe Bend.*—Wrinkle bending consists in heating with the oxyacetylene flame one or more narrow bands at right angles to the pipe and extending about halfway around the pipe. The pipe is then bent either by hand or by means of a tractor or some suitable bending rig until the heated sections buckle sufficiently to give the pipe the desired curvature.

Wrinkle bending is analogous to shop-fabricated creased bends, only the wrinkle or crease is not so pronounced. As a rule, each wrinkle is used to produce only a slight change in direction of the pipe. When the bend is more pronounced, a series of wrinkles are used to give a long sweep bend. The wrinkles project outward, thus providing a full opening inside the pipe throughout the bend. Wrinkle bending is applicable to all sizes of pipe from the smallest to the largest. The method is adaptable to both heavy

wall and light wall pipe and can be performed in the shop as easily as in the field.

(*b*) *Application to Pipe Lines.*—The advantages of wrinkle bending are many. Particularly important is that the pipe wall is practically never thinned from the original thickness. On the contrary, compression squeezes the pipe so that the metal at the wrinkle is actually slightly thicker than the original wall. The metal on the outside of the bend opposite the wrinkle retains its original thickness.

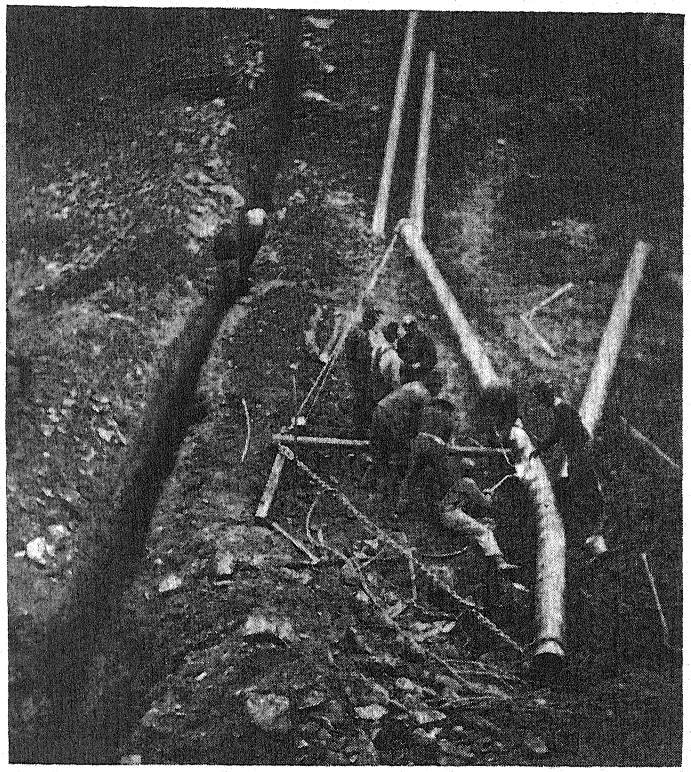


Fig. 17—Making Sag on Overland Pipe Line by Wrinkle Bending

Wrinkle bending lends itself readily to correction since too much bending in one or more wrinkles may be corrected simply by reheating and applying a reverse pull or sag. Furthermore, the pipe is not stressed as in cold bending because the bend takes place only at the point where the steel has been softened by heating.

Another important feature of wrinkle bending is its low cost. Equipment costs, labor costs and materials costs are all low. Also, the method permits bending even before the ditch is cut. Wrinkle bending fits in very well with the all-bell-hole or stab-on methods of welding.

(*c*) *Procedure for Small Diameters.*—As a rule, only one oxyacetylene blowpipe is required for wrinkle bending pipe under 6 in. The large-capacity blowpipes designed for heavy heating operations are particularly suitable for wrinkle bending. Skilled welding operators are not required, as the process involves only a simple heating operation.

If the pipe is of small diameter, 6 in. for instance, no additional bending equipment is necessary. The section of pipe is laid on skids across the ditch and the foreman marks the point at which the pipe is to be bent. The heaters, standing on each side of the pipe, then proceed to apply heat to this point around approximately one-half to two-thirds of the upper circumference of the pipe. The band of heat should be 2 to 3 in. wide at the top of the pipe and should taper down to zero on the two sides. The pipe should be heated to a bright red.

When the pipe is at the correct temperature, the section should be rolled over quickly so that the heated portion is on the underside. At the same time, one of the pipe gang should throw the skid on which one end of the pipe is resting into the ditch. This man should then press, if necessary, on his end of the pipe while the other end is being held securely by two additional men. The weight of the pipe itself is usually sufficient to form the wrinkle and the man in the ditch often finds his chief work in holding the sagging pipe to the requirements of the bend.

This operation is repeated until sufficient wrinkles have been formed to give the required bend. In general, a wrinkle of 5 to 7° should be the maximum to which the pipe is bent. The entire procedure for each wrinkle should not require more than $2^1/_2$ to 3 min.

(*d*) *Procedure for Large Pipe.*—Two blowpipes should be used for wrinkle bending pipe 6 in. in diameter and over. Also, additional bending equipment is necessary if the pipe is large or lying alongside the ditch or on the ground prior to ditching. A tractor, A-frame or bending rig can be used (see Fig. 17). If a tractor is used, it should be equipped with a stiff leg derrick. The tractor should run part way onto the timbers which hold the pipe in place, the stiff leg set in position and the chain block attached. The chain block in turn is fastened to the pipe. The pipe should then be heated in the usual manner with the two blowpipes and when the proper heat is reached the free end should be pulled up by means of the chain block.

Another method for handling this type of work is to use a tripod or A-frame equipped with block and tackle. One end of the pipe should be temporarily anchored, the heat applied, and the free end then hoisted to form the wrinkle. Still another method using the same equipment is to hoist the pipe first, place one or two men at one end to steady the pipe and one or two men at the other end to press down. Heat is then applied on the underside of the section and the wrinkle is formed by the weight of the sagging pipe.

Pipe Cutting

One of the indispensable tools in welded pipe-line construction, as in all steel fabrication, is the oxyacetylene cutting torch. It is used for removing questionable welds, for checking the operators, for fabrication of headers and for cutting of outlet openings, bull plugs and other such fittings. Automatic and semi-automatic pipe-cutting machines are available for

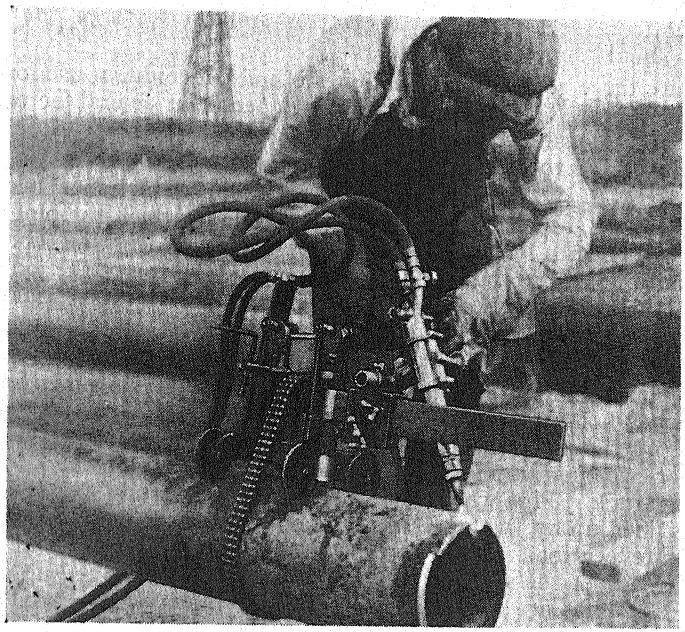


Fig. 18—Beveling Reclaim Pipe for Relaying

accurately cutting and beveling the pipe for welding (see Fig. 18). These are extensively used for cutting up and reclaiming old pipe lines as well as for new construction.

Qualification of Welding Operators

Usually the ability of the welding operators is determined by field qualification tests. A typical oil field qualification test consists in making horizontal pipe position welds on short sections of the line pipe. If the job is large enough to differentiate between "roll" weld operators and position weld operators, then tests are given for these various positions and operators are only permitted to weld on those positions for which they have qualified. From the finished weld sample, coupons 1 to $1^1/_2$ in. wide (called "straps" in the oil fields) are cut with a torch and given tensile and bend tests in a portable tensile and bend-testing machine. An applicant having a coupon fail in the weld at less than 90% of the pipe strength is generally disqualified.

Equipment and Welding Organization

The welding and construction organization will necessarily be dependent upon the type of pipe line, its location, length, time limit of construction, coordination of the different construction gangs, contour of the pipe line, right-of-way and other factors. In any case, the organization should include operators skilled in making both rotation and overhead welds and in cutting accurately to a line and beveling with the torch or blowpipe. A man

competent to inspect materials, apparatus and the work of the welding operators should supervise the job.

There are three general construction methods in common use for solidly welded pipe lines. The choice of methods depends on several factors, some of the more important being length of line, equipment and workmen available, time allowed to complete the line, and terrain.

Rotation (Roll) Welding Method.—The method which has been most widely employed, especially for long lines, is one in which the pipe lengths are first welded into long sections, usually 200 ft. in length. The pipe is turned continuously so that welding is done near the top of the joint. The 200-ft. sections are then bent to fit the ditch and are tied in to make a continuous line. The tie-in welds required between these sections are made as fixed, since the pipe cannot then be turned.

The typical welding organization consists of a line-up gang, firing-line gang and bell-hole gang. For a 6-in. line or a light wall 8-in. line, the gang for lining up the pipe will usually consist of a foreman, 10 to 20 laborers and one or two operators for tack welding the joints. Skids and dollies are hauled by truck. Pipe which has been previously strung along the right-of-way is lined up by two or four workmen. They set skids and dollies in approximate locations. Other workmen set the 40-ft. lengths of pipe in the dollies and adjust the skids so that the pipe lengths are lined up straight. Five 40-ft. lengths are generally lined up in a single string or roll. Other workmen space the pipe joints accurately for the operator who tack welds each joint in two or more places.

The gang making the rolling welds, known as the firing-line gang, consists usually of a welding foreman, four welding operators, one spell-off operator, four pipe turners, two generator men, two generator wagons with teams and drivers and one water and material truck with a driver. Two operators obtain their gases from a single generator wagon, but work on individual rolls of pipe for most efficient results. The generator men keep the operators supplied with welding rod and change oxygen cylinders when necessary, as well as take care of the generators.

Directly with and behind the bending crew is the bell-hole gang, which consists essentially of an operator for tack welding, from two to three operators for bell-hole welding and a generator man for each generator provided.

Such a welding organization can take care of from $2^1/_4$ to 3 miles of line daily, depending on the pipe size and condition of the right-of-way.

Additional men may be provided for larger pipe. For fairly high production of the firing line, six welding operators are put on in place of four, requiring additional pipe turners and another generator with generator man, wagon, team and driver.

Stove-Pipe Welding Method.—The second method in fairly wide use is suitable for both long and short lines. The daily mileage possible with one gang is usually not as great as with the first method. Instead of welding the 40-ft. lengths of pipe into 200-ft. sections, the individual lengths are handled separately in tying in the line. Pipe lengths are bent to fit the ditch, where this is necessary, joints are aligned and tack welded, and every weld is made as a fixed weld.

What it really amounts to is the elimination of the usual line-up and

firing-line gangs, with the bending or tie-in gang handling sections 40 ft. long instead of the usual 200 ft. Naturally the bell-hole welding crew must be considerably increased.

The procedure usually followed is to line the pipe up high on skids over the ditch, dug in advance, after which the joints are tack welded and welded without turning the pipe. Bends needed are made in various ways, depending on equipment available. Besides the operator who makes the tack welds, from three to six or more operators are assigned to do the bell-hole welding, depending on the speed with which the pipe can be lined up.

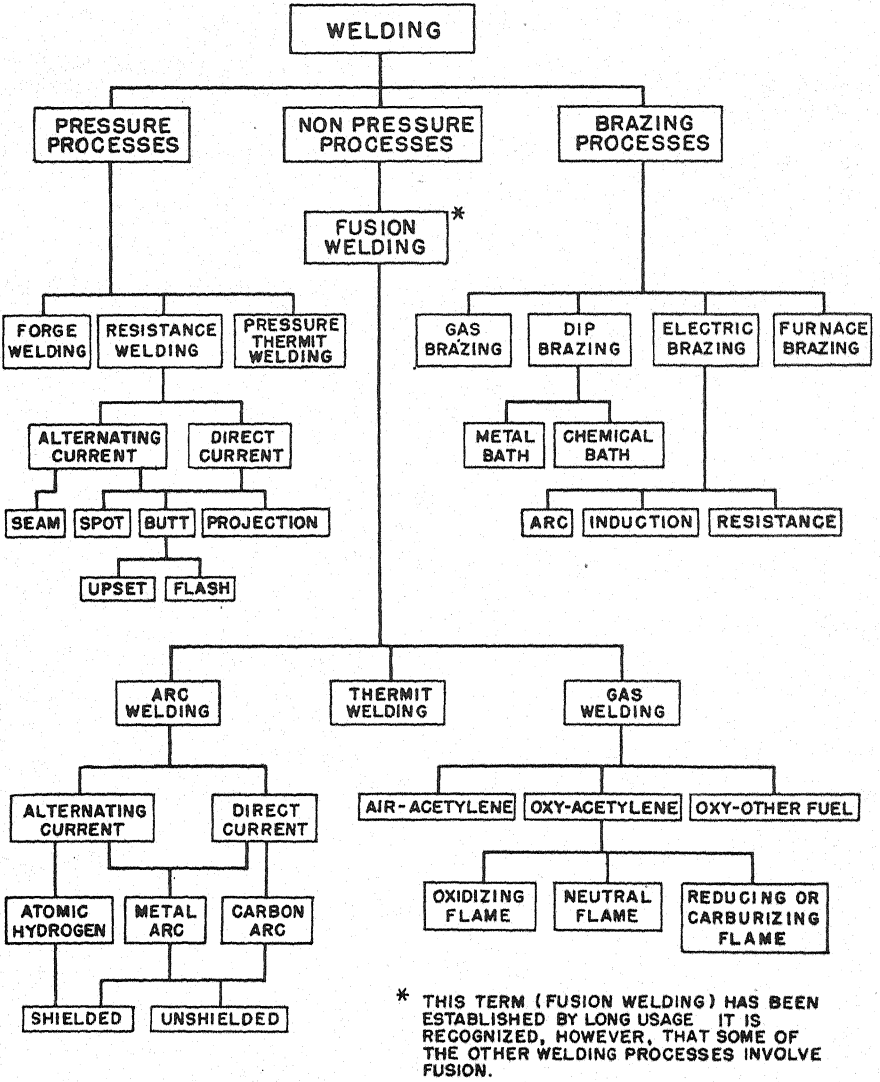
Over-all costs, taking into account bending, lining up pipe over the ditch, tack welding and overhead welding of each joint, are comparable to costs for equivalent operations where a firing-line gang is employed. Costs are almost always less for the all-bell-hole method on short jobs because of the smaller amount of equipment needed. Supervision is also greatly simplified.

Stove-Pipe Alternative Method.—The third method is a variation of the second. Pipe lengths are bent where necessary, joints are aligned but are not tack welded. Instead, two operators commence welding on opposite sides and complete the weld without the pipe being turned, after which another length of pipe is aligned and the process repeated. Daily weld production is limited to the number of welds that can be made by two operators. This method is suited to short lines because a minimum of equipment and workmen are needed.

CHAPTER 42

DEFINITIONS AND CHART

MASTER CHART OF WELDING PROCESSES



* THIS TERM (FUSION WELDING) HAS BEEN ESTABLISHED BY LONG USAGE IT IS RECOGNIZED, HOWEVER, THAT SOME OF THE OTHER WELDING PROCESSES INVOLVE FUSION.

INDEX TO DEFINITIONS OF WELDING TERMS

The definitions in this chapter are divided into the following groups: Group I—General, Group II—Types of Joints and Welds, Group III—Details of Joints and Welds, Group IV—Arc Welding, Group V—Gas Welding, Group VI—Resistance Welding, Group VII—Brazing, Group VIII—Thermit Welding, Group IX—Forge Welding, Group X—Arc and Oxygen Cutting, and Group XI—Testing and Inspection.

To facilitate reference an alphabetical index to these definitions is given below.

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DEFINITIONS OF WELDING TERMS*

GROUP I—GENERAL

A. Welding Processes

Note: The relationship of the various welding processes one to another is shown in the Master Chart of Welding Processes on page 1524.

Pressure Welding: A group of welding processes wherein the weld is consummated by pressure.

Non-Pressure Welding: A group of welding processes wherein the weld is made without pressure.

Fusion Welding: A group of processes in which metals are welded together by bringing them to the molten state at the surfaces to be joined, with or without the addition of filler metal, without the application of mechanical pressure or blows.

Brazing: A group of welding processes wherein the filler metal is a nonferrous metal or alloy whose melting point is higher than 1000° F. but lower than that of the metals or alloys to be joined.

Hard Surfacing: The application of a hard, wear-resistant alloy to the surface of a softer metal, by an arc or gas welding process.

B. Materials and Equipment

Filler Metal: Metal to be added in making a weld.

Flux: A fusible material or gas used to dissolve and prevent the formation of oxides, nitrides or other undesirable inclusions formed in welding.

Filter Lens: A colored glass used in goggles, helmets and shields to exclude harmful light rays.

Cover Glass: A clear glass used to protect the lens in goggles, face shields and helmets from spattering material.

C. Welding Details

Welding Operator: An operator of welding equipment.

Weldment: An assembly whose component parts are joined by welding.

Flat Position of Welding: A position of welding in which filler metal is deposited from the upper side of the joint and the face of the weld is approximately horizontal. The limits of this position are defined in Figures 1 and 1A.

* A Standard of the AMERICAN WELDING SOCIETY.

Horizontal Position of Welding:

(*a*) *Fillet Weld:* A position of welding in which the weld is deposited on the upper side of an approximately horizontal surface and against an approximately vertical surface. The limits of this position are defined in Figure 1.

(*b*) *Groove Weld:* A position of welding in which the axis of the weld lies in an approximately horizontal plane and the face of the weld lies in an approximately vertical plane. The limits of this position are defined in Figure 1A.

Vertical Position of Welding: A position of welding in which the axis of the weld is approximately vertical. The limits of this position are defined in Figures 1 and 1A.

Overhead Position of Welding: A position of welding in which filler metal is deposited from the under side of the joint and the face of the weld is approximately horizontal. The limits of this position are defined in Figures 1 and 1A.

Welding Procedure: The detailed methods and practices involved in the production of a welded structure.

Manual Welding: Welding wherein the arc is controlled or the torch is manipulated by hand.

Automatic Welding: Welding with equipment which automatically controls the entire welding operation. (Including feed, speed, oscillation, interruption, etc.)

Welding Sequence: The order of welding the component parts of a structure.

Back-Step Sequence: A welding technique wherein the increments of weld metal are deposited opposite to the direction of progression.

Build-Up Sequence: The method of depositing a multiple pass weld with respect to its cross section.

Pass Sequence: The method of depositing a weld with respect to its length.

Preheating: Heat applied prior to welding or cutting operations.

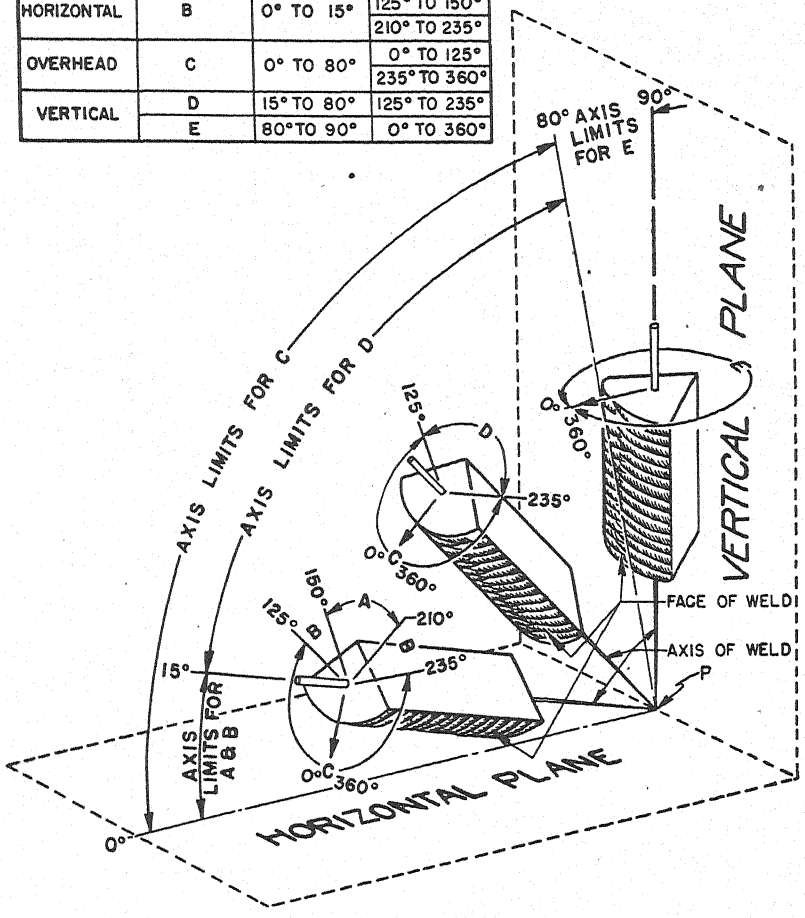
Concurrent Heating: Supplemental heat applied to a structure during the course of welding.

Postheating: Heat applied subsequently to welding or cutting operations.

Thermal Stress: Stress produced in a structure or member caused by differences in temperature or coefficients of expansion.

Residual Stress: Stress remaining in a structure or member as a result of thermal or mechanical treatment, or both.

TABULATION OF POSITIONS OF FILLET WELDS			
POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	125° TO 150°
			210° TO 235°
OVERHEAD	C	0° TO 80°	0° TO 125°
			235° TO 360°
VERTICAL	D	15° TO 80°	125° TO 235°
	E	80° TO 90°	0° TO 360°



NOTE I :

THE HORIZONTAL REFERENCE PLANE IS TAKEN TO LIE ALWAYS BELOW THE WELD UNDER CONSIDERATION.

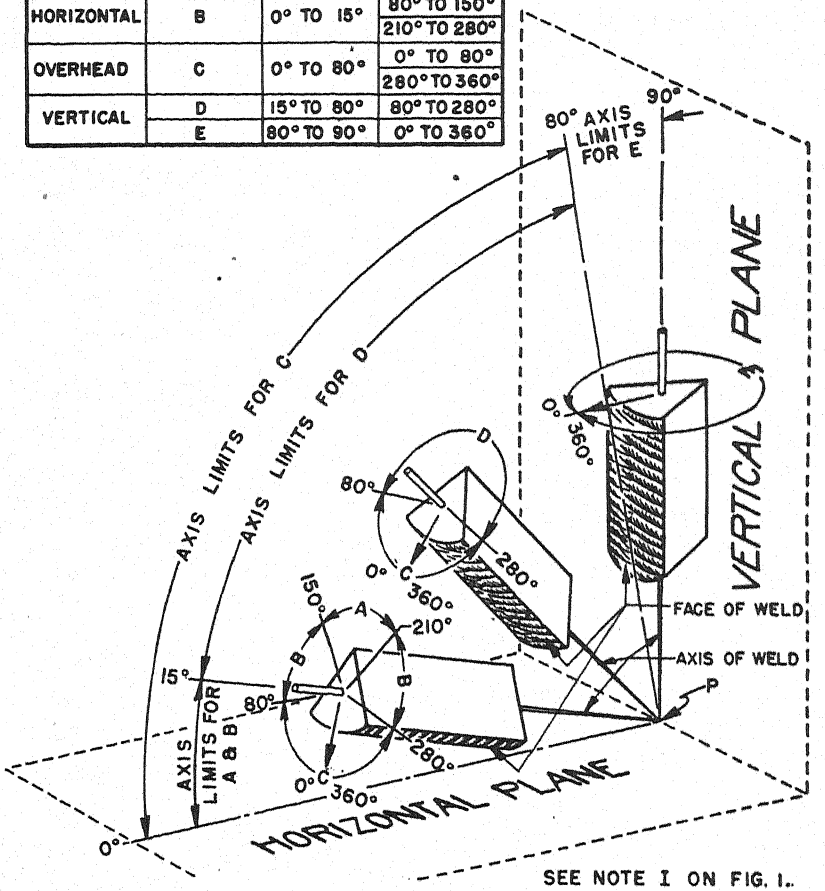
INCLINATION OF AXIS IS MEASURED FROM THE HORIZONTAL REFERENCE PLANE TOWARD THE VERTICAL.

ANGLE OF ROTATION OF FACE IS MEASURED FROM A LINE PERPENDICULAR TO THE AXIS OF THE WELD AND LYING IN A VERTICAL PLANE CONTAINING THIS AXIS, THE REFERENCE POSITION (0°) OF ROTATION OF THE FACE INVARIABLY POINTS IN THE DIRECTION OPPOSITE TO THAT IN WHICH THE AXIS ANGLE INCREASES. THE ANGLE OF ROTATION OF THE FACE OF WELD IS MEASURED IN A CLOCKWISE DIRECTION FROM THIS REFERENCE POSITION (0°) WHEN LOOKING AT POINT P.

POSITIONS OF FILLET WELDS

FIG. 1

TABULATION OF POSITIONS OF GROOVE WELDS			
POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	80° TO 150°
			210° TO 280°
OVERHEAD	C	0° TO 80°	0° TO 80°
			280° TO 360°
VERTICAL	D	15° TO 80°	80° TO 280°
	E	80° TO 90°	0° TO 360°



SEE NOTE I ON FIG. 1.

NOTE I: PIPE WELDING POSITIONS - GROOVE WELDS

FOR GROOVE WELDS IN PIPE THE FOLLOWING DEFINITIONS SHALL APPLY.

HORIZONTAL FIXED POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 30° FROM THE HORIZONTAL PLANE AND THE PIPE IS NOT ROTATED DURING WELDING.

HORIZONTAL ROLLED POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 30° FROM THE HORIZONTAL PLANE, THE PIPE IS ROTATED DURING WELDING, AND THE WELD METAL IS DEPOSITED WITHIN AN ARC NOT TO EXCEED 15° ON EITHER SIDE OF A VERTICAL PLANE PASSING THROUGH THE AXIS OF THE PIPE.

VERTICAL POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 10° FROM THE VERTICAL POSITION (THE PIPE MAY OR MAY NOT BE ROTATED DURING WELDING.)

POSITIONS OF GROOVE WELDS
FIG. 1A.

Stress Relief Heat Treatment: Uniform heating of a structure or portion thereof to a sufficient temperature, below the critical range, to relieve the major portion of the residual stresses, followed by uniform cooling. (NOTE: Terms normalizing, annealing, etc., are misnomers for this application.)

Peening: The mechanical working of metal by means of hammer blows

Rate of Deposition: The weight of metal deposited in a unit of time.

GROUP II—TYPES OF JOINTS AND WELDS

A. Welded Joints

Welded Joint: A localized union of two or more parts by welding.

Butt Joint: A welded joint between two abutting parts lying in approximately the same plane. See Figure 2.

Single-Welded Butt Joint: A butt joint welded from one side only.

Double-Welded Butt Joint: A butt joint welded from both sides.

Lap Joint: A welded joint in which two overlapping parts are connected by means of fillet, plug, slot, spot, projection or seam welds. See Figure 5.

Single-Welded Lap Joint: A lap joint in which the overlapped edges of the members to be joined are welded along the edge of one member.

Double-Welded Lap Joint: A lap joint in which the overlapped edges of the members to be joined are welded along the edges of both members.

Tee Joint: A welded joint at the junction of two parts located approximately at right angles to each other in the form of a T. See Figure 6.

Corner Joint: A welded joint at the junction of two parts located approximately at right angles to each other in the form of an L. See Figure 3.

Edge Joint: A welded joint connecting the edges of two or more parallel or nearly parallel parts. See Figure 4.

Composite Joint: A joint wherein welding is used in conjunction with a mechanical joint.

B. Welds*

Weld: A localized consolidation of metals by a welding process.

Groove Weld: A weld made by depositing filler metal in a groove between two members to be joined. The standard types of groove welds are listed below:

(*a*) Square Groove Weld (illustrated in Figure 7)
(*b*) Single-Vee Groove Weld (illustrated in Figure 8)

* The various types of resistance welds are listed in Group VI-B, page 1547.

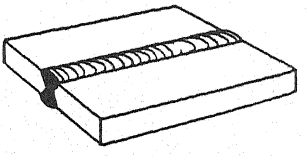


Fig. 2—Butt Joint

Types of Welds Applicable to Butt Joints
- Square Groove
- Single-V Groove
- Double-V Groove (Illustrated)
- Single Bevel Groove
- Double Bevel Groove
- Single-U Groove
- Double-U Groove
- Single-J Groove
- Double-J Groove
- Butt (Resistance)

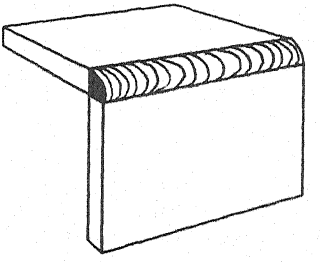


Fig. 3—Corner Joint

Types of Welds Applicable to Corner Joints
- Fillet (Illustrated)
- Square Groove
- Single-V Groove
- Single Bevel Groove
- Double Bevel Groove
- Single-U Groove
- Single-J Groove
- Double-J Groove
- Projection (Resistance)

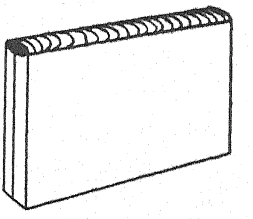


Fig. 4—Edge Joint

Types of Welds Applicable to Edge Joints
- Bead (Illustrated)
- Single-V Groove
- Single-U Groove

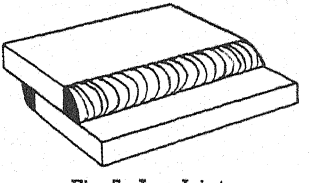


Fig. 5—Lap Joint

Type of Welds Applicable to Lap Joints
- Fillet (Illustrated)
- Plug
- Slot
- Spot (Resistance)
- Seam (Resistance)
- Projection (Resistance)

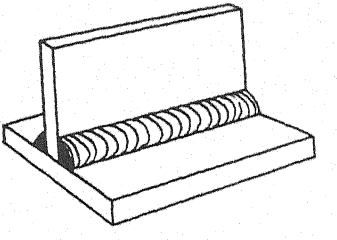


Fig. 6—Tee Joint

Types of Welds Applicable to Tee Joints
- Fillet (Illustrated)
- Single Bevel Groove
- Double Bevel Groove
- Single-J Groove
- Double-J Groove

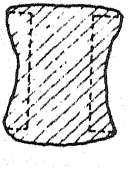


Fig. 7—Square Groove Weld

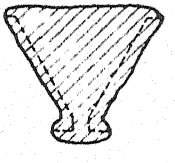


Fig. 8—Single-V Groove Weld

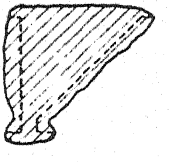


Fig. 9—Single Bevel Groove Weld

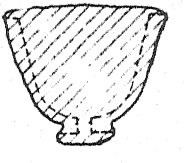


Fig. 10—Single-U Groove Weld

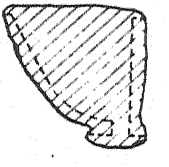


Fig. 11—Single-J Groove Weld

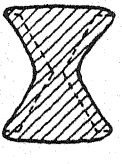


Fig. 12—Double-V Groove Weld

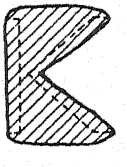


Fig. 13—Double Bevel Groove Weld

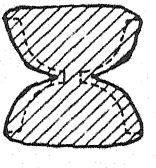


Fig. 14—Double-U Groove Weld

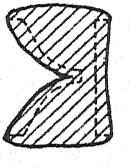


Fig. 15—Double-J Groove Weld

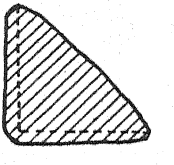
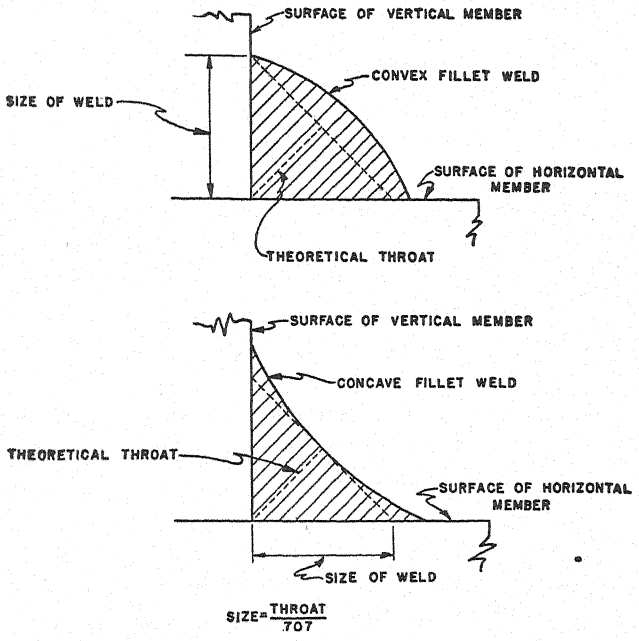


Fig. 16—Fillet Weld



NOTE:
THE SIZE OF A FILLET WELD IS THE LEG LENGTH OF THE LARGEST INSCRIBED ISOSCELES RIGHT TRIANGLE.

Fig. 17—Details of Fillet Weld

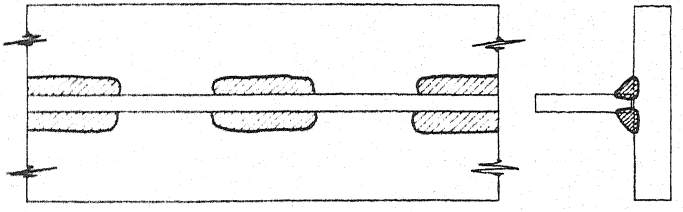


Fig. 18—Chain Intermittent Fillet Welds

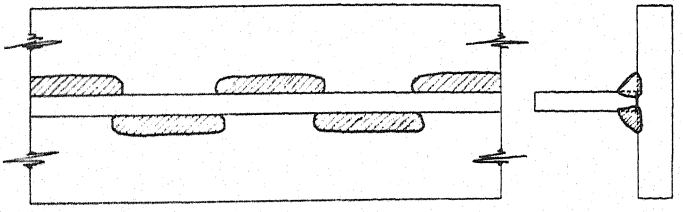


Fig. 19—Staggered Intermittent Fillet Welds

(*c*) Single-Bevel Groove Weld (illustrated in Figure 9)
(*d*) Single-U Groove Weld (illustrated in Figure 10)
(*e*) Single-J Groove Weld (illustrated in Figure 11)
(*f*) Double-Vee Groove Weld (illustrated in Figure 12)
(*g*) Double-Bevel Groove Weld (illustrated in Figure 13)
(*h*) Double-U Groove Weld (illustrated in Figure 14)
(*i*) Double-J Groove Weld (illustrated in Figure 15)

Fillet Weld: A weld of approximately triangular cross section, as used in a lap joint, tee joint or corner joint joining two surfaces approximately at right angles to each other. See Figure 16 and also Figures 3, 5 and 6.

Concave Fillet Weld: A fillet weld having a concave face. See Figure 17.

Convex Fillet Weld: A fillet weld having a convex face. See Figure 17.

Full Fillet Weld: A fillet weld whose size is equal to the thickness of the thinner member joined.

Chain Intermittent Fillet Welds: Two lines of intermittent fillet welding in a tee or lap joint, in which the increments of welding in one line are approximately opposite to those in the other line. See Figure 18

Staggered Intermittent Fillet Welds: Two lines of intermittent fillet welding in a tee or lap joint, in which the increments of welding in one line are staggered with respect to those in the other line. See Figure 19.

Bead Weld: A type of weld made by one passage of electrode or rod See Figure 20 and also Figure 4.

Plug Weld: A weld made in a hole in one member of a lap joint, joining that member to that portion of the surface of the other member which is exposed through the hole. The walls of the hole may or may not be parallel, and the hole may be partially or completely filled with weld metal. See Figure 21.

Slot Weld: A weld made in an elongated hole in one member of a lap joint, joining that member to that portion of the surface of the other member which is exposed through the hole. The hole may be open at one end, i.e., may extend to the edge of the member, and may or may not be filled completely with weld metal. See Figure 22.

Tack Weld: A weld used for assembly purposes only.

Seal Weld: A weld used primarily to obtain tightness and prevent leakage.

Continuous Weld: A weld which extends continuously for its entire length.

Intermittent Weld: A weld whose continuity is brokenby unwelded spaces.

Flush Weld: A weld made with a minimum reinforcement.

GROUP III—DETAILS OF JOINTS AND WELDS

A. Joint Details

Edge Preparation: A prepared contour on the edge of a part to be joined by a groove weld. See Figure 23.

Groove: The opening provided between two members to be joined by a groove weld. See Figure 24.

Groove Angle: The total included angle of the groove between parts to be joined by a groove weld. See Figure 25.

Bevel Angle: The angle of bevel on the prepared edge of a part to be joined by a groove weld. See Figure 26.

Root Edge: The edge of the part to be welded which is adjacent to the root. See Figure 27.

Root Face: The portion of the prepared edge of a part to be joined by a groove weld, which has not been beveled or grooved. See Figure 28.

Root Radius: The radius near the root portion of the prepared edge of a part to be joined by a U- or J-groove weld. See Figure 29.

Root Opening: The separation at the root between parts to be joined by a groove weld. See Figure 30.

Backing: Material (metal, asbestos, carbon, etc.) backing up the root of the weld. Frequently this material is in the form of a "backing strip" or "backing ring" used to back up the root of a groove weld in plate and pipe, respectively.

Faying Surface: That surface of the base metal which comes in contact with another part of base metal to which it is fastened.

B. Weld Details

Base Metal: The metal to be welded or cut.

Filler Metal: Material to be added in making a weld.

Weld Metal: The metal resulting from the fusion of the base metal or the base metal and the filler metal.

Deposited Metal: Metal that has been added by a welding process.

Bond: The junction of the weld metal and the base metal.

Penetration: The penetration, or depth of fusion, of a weld is the distance from the original surface of the base metal to that point at which fusion ceases. See Figure 31.

Heat-Affected Zone: That portion of the base metal whose structure or properties have been altered by the heat of welding or cutting.

Unaffected Zone: That portion of the base metal outside of the heat-affected zone, wherein no change in physical properties or microstructure has taken place.

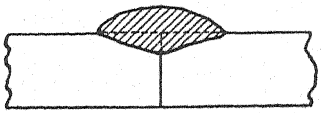


Fig. 20—Bead Weld

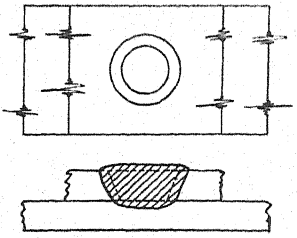


Fig. 21—Plug Weld

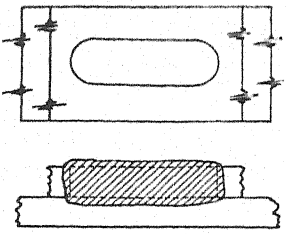


Fig. 22—Slot Weld

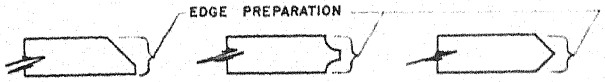


Fig. 23—Edge Preparation

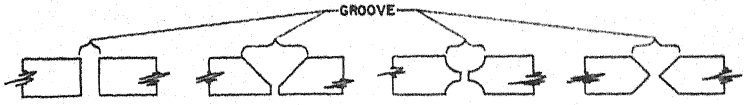


Fig. 24—Groove

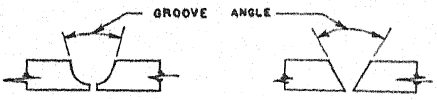


Fig. 25—Groove Angle

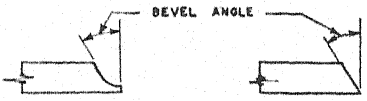


Fig. 26—Bevel Angle

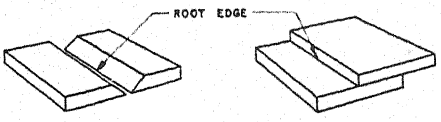


Fig. 27—Root Edge

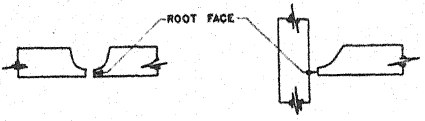


Fig. 28—Root Face

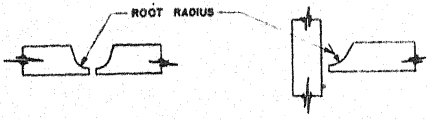


Fig. 29—Root Radius

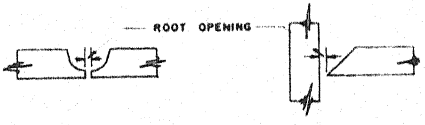


Fig. 30—Root Opening

Pass: The weld metal deposited by one general progression along the axis of a weld. See Figure 32.

Layer: A stratum of weld metal consisting of one or more passes. See Figure 33.

Root of Weld: The point at the bottom of the weld. See Figure 34.

Face of Weld: The exposed surface of a weld. See Figure 35.

Toe of Weld: The junction between the face of the weld and the base metal. See Figure 36.

Reinforcement of Weld: Weld metal on the face of a weld, in excess of that required for the size of weld specified. See Figure 37.

Crater: A depression at the termination of an arc weld.

Axis of a Weld: A line through the weld parallel to the root. See Figure 1 or 1A.

Effective Length of Weld: The length of the correctly proportioned cross section of a weld.

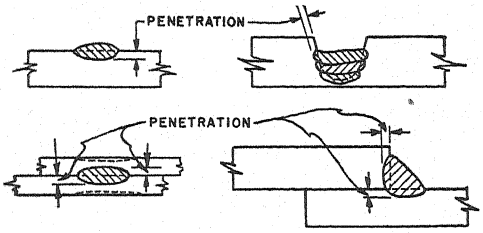


Fig. 31—Penetration

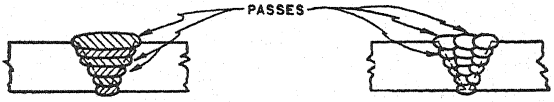


Fig. 32—Passes

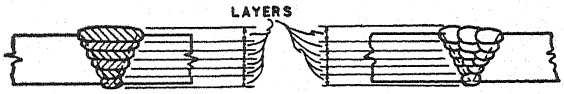


Fig. 33—Layers

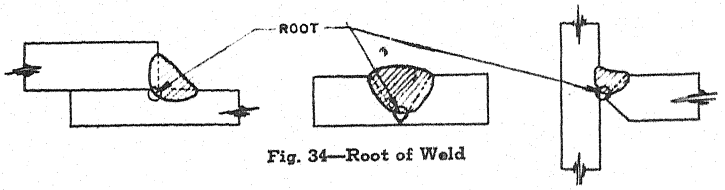


Fig. 34—Root of Weld

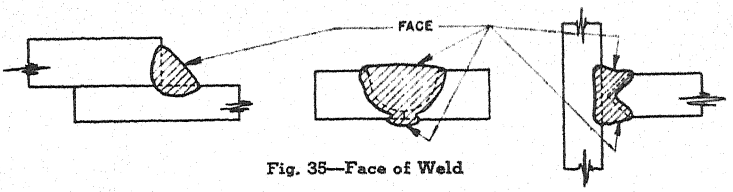


Fig. 35—Face of Weld

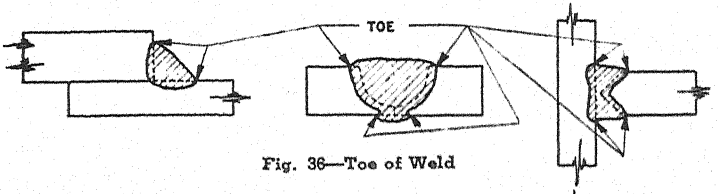


Fig. 36—Toe of Weld

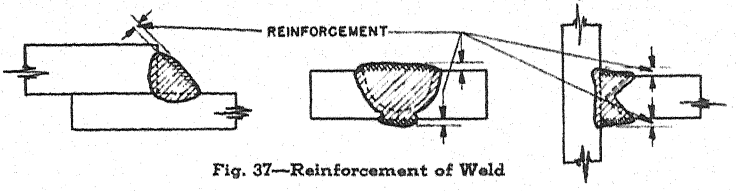


Fig. 37—Reinforcement of Weld

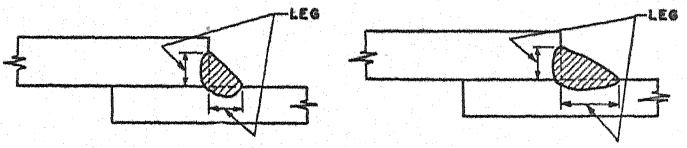


Fig. 38—Leg of Fillet Weld

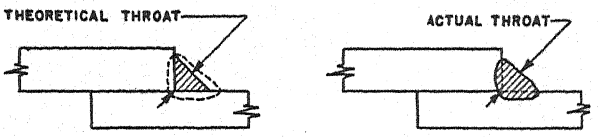


Fig. 39—Throat of Fillet Weld

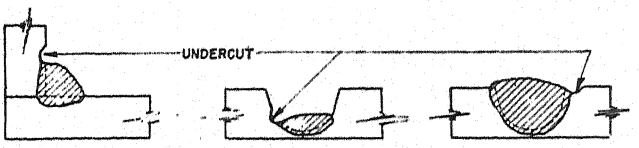


Fig. 40—Undercutting

Size of Weld:

(*a*) *Fillet Weld:* The size of a fillet weld is the leg length of the largest inscribed isosceles right triangle. See Figure 17.

(*b*) *Groove Weld:* The size of a groove weld is the depth of the groove. Where fusion materially exceeds the groove depth, the size of the weld is the depth of the groove plus the depth of fusion.

Leg of Fillet Weld: The distance from the point where the original surfaces intersected, to the toe of the fillet. See Figure 38.

Throat of Fillet Weld (Actual Throat): The distance from the root to the face of the weld. See Figure 39.

Theoretical Throat of Fillet Weld: The distance from the root to the hypotenuse of the largest isosceles right triangle that can be inscribed within the weld cross section. See Figure 39.

C. Weld Defects

Porosity: The presence of gas pockets or inclusions.

Gas Pocket: A cavity in a weld caused by gas inclusion.

Slag Inclusion: Non-metallic material entrapped in a weld.

Overlap: Protrusion of weld metal at the toe of a weld beyond the limits of fusion.

Undercut: A groove melted into the base metal adjacent to the toe of the weld and left unfilled. See Figure 40.

GROUP IV—ARC WELDING

A. Welding Processes

Arc Welding: A non-pressure (fusion) welding process wherein the welding heat is obtained from an arc either between the base metal or weld metal and an electrode, or between two electrodes.

Alternating Current Arc Welding: An arc welding process wherein the power supply at the arc is alternating current.

Direct Current Arc Welding: An arc welding process wherein the power supply at the arc is direct current.

Metal Arc Welding: An arc welding process wherein the electrode supplies the filler metal in the weld.

Shielded Metal Arc Welding: A metal arc welding process wherein the arc and weld metal are protected from the atmosphere by a shielding medium.

Unshielded Metal Arc Welding: A metal arc welding process wherein no shielding medium is used.

Carbon Arc Welding: An arc welding process wherein one or more carbon or graphite electrodes are used, with or without the use of filler metal.

Shielded Carbon Arc Welding: A carbon arc welding process wherein the arc and molten weld metal are protected from the atmosphere by a shielding medium.

Unshielded Carbon Arc Welding: A carbon arc welding process wherein no shielding medium is used.

Atomic Hydrogen Welding: An alternating current arc welding process wherein the welding heat is obtained from an arc between two suitable electrodes in an atmosphere of hydrogen.

B. Materials and Equipment

Arc Welder: An arc welding machine. (The term "welder" has sometimes been used to denote an operator of welding equipment, for which the term Welding Operator is greatly to be preferred.)

Filler Metal: Metal to be added in making a weld.

Welding Rod: Filler metal, in wire or rod form, used in the gas welding process and those arc welding processes wherein the electrode does not furnish the deposited metal.

Electrode:

(*a*) *Metal Arc:* Filler metal in the form of a wire or rod, either bare or covered, through which current is conducted between the electrode holder and the arc.

(*b*) *Carbon Arc:* A carbon or graphite rod through which current is conducted between the electrode holder and the arc.

(*c*) *Atomic Hydrogen:* One of two tungsten rods between the points of which the arc is maintained.

Bare (Lightly Coated) Electrode: A solid metal electrode with no coating other than that incidental to the manufacture of the electrode, or with a light coating.

Covered (Shielded Arc) Electrode: A metal electrode which has a relatively thick covering material serving the dual purpose of stabilizing the arc and improving the properties of the weld metal.

Composite Electrode: An electrode with or without a flux, having more than one filler material combined mechanically.

Electrode Holder: A device used for mechanically holding the electrode.

Welding Leads: Conductors furnishing an electrical path between the source of welding power and the electrodes.

Hand Shield: A protective device used in arc welding for shielding the face and neck, equipped with a suitable filter glass lens and designed to be held by hand.

Helmet Shield: A protective device used in arc welding for shielding the face and neck, equipped with a suitable filter glass lens and designed to be worn on the head.

Filter Lens: A colored glass used in goggles, helmets and shields to exclude harmful light rays.

Cover Glass: A clear glass used to protect the lens in goggles, face shields and helmets from spattering material.

C. Welding Details

Arc Voltage: The voltage across the arc.

Straight Polarity (Electrode Negative): The arrangement of direct current arc welding leads wherein the work is the positive pole and the electrode is the negative pole of the arc circuit.

Reversed Polarity (Electrode Positive): The arrangement of direct current arc welding leads wherein the work is the negative pole and the electrode is the positive pole in the arc circuit.

Welding Ground: The side of the circuit opposite the welding electrode.

Melting Rate: The weight or length of electrode consumed in a unit of time.

Spatter Loss: The difference in weight between the weight of electrode deposited and the weight of the electrode consumed (melted).

Deposition Efficiency: The ratio of the weight of deposited metal to the net weight of the electrodes consumed (exclusive of stubs).

Beading: A technique of depositing weld metal without oscillation of the electrodes, which generally results in a relatively narrow pass. See Figure 41.

Weaving: A technique of depositing weld metal in which the electrode is oscillated. See Figure 42.

Semi-Automatic Metal Arc Weld: A weld made with equipment which automatically controls the feed of the electrode, the manipulation of the electrode being controlled by hand.

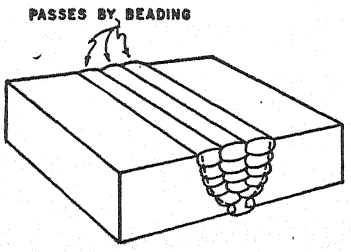


Fig. 41—Beading

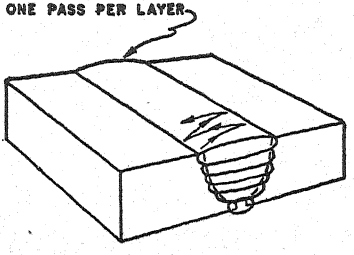


Fig. 42—Weaving

GROUP V—GAS WELDING

A. Welding Processes

Gas Welding: A non-pressure (fusion) welding process wherein the welding heat is obtained from a gas flame.

Air-Acetylene Welding: A gas welding process wherein the welding heat is obtained from the combustion of air and acetylene.

Oxy-Acetylene Welding: A gas welding process wherein the welding heat is obtained from the combustion of oxygen and acetylene.

Oxy-Other Fuel Gas Welding: A gas welding process wherein the welding heat is obtained from the combustion of oxygen and any fuel gas other than acetylene.

B. Materials and Equipment

Welding Rod: Filler metal, in wire or rod form, used in the gas welding process and those arc welding processes wherein the electrode does not furnish the deposited metal.

Flux: A fusible material or gas used to dissolve and prevent the formation of oxides, nitrides or other undesirable inclusions formed in welding.

Welding Torch or Blowpipe: A device used in gas welding for mixing and controlling the gases.

Welding Tip: A gas torch tip especially adapted for welding.

Mixing Chamber: That part of a gas welding or cutting torch wherein the gases are mixed for combustion.

Cylinder: A portable container used for storage of a compressed gas.

Manifold: A multiple header for connection of individual gas cylinders or torch supply lines.

C. Welding Details

Neutral Flame: A gas flame wherein the portion used is neither oxidizing nor reducing. See Figure 43.

Oxidizing Flame: A gas flame wherein the portion used has an oxidizing effect. See Figure 44.

Reducing Flame: A gas flame wherein the portion used has a reducing effect. See Figure 45.

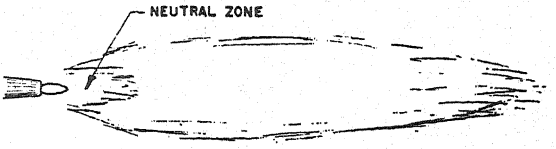
Carburizing Flame: A gas flame having the property of introducing carbon into the metal heated.

Cone: The conical part of a gas flame which is next to the orifice of the tip.

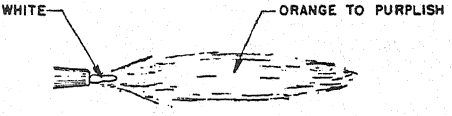


FLAME AS SEEN WITHOUT WELDERS GOGGLES

Fig. 43
Neutral Flame

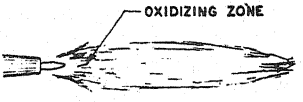


FLAME AS SEEN WITH WELDERS GOGGLES

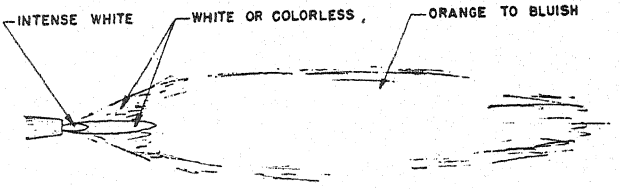


FLAME AS SEEN WITHOUT WELDERS GOGGLES

Fig. 44
Oxidizing Flame

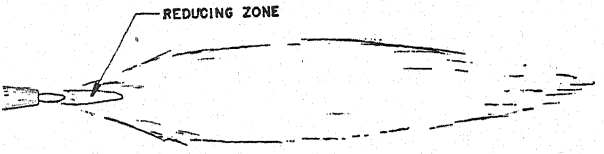


FLAME AS SEEN WITH WELDERS GOGGLES



FLAME AS SEEN WITHOUT WELDERS GOGGLES.

Fig. 45
Reducing Flame



FLAME AS SEEN WITH WELDERS GOGGLES.

Backfire: The momentary recession of the flame into the torch tip followed by immediate reappearance or complete extinguishment.

Flashback: A recession of the flame into or back of the mixing chamber of the torch.

Rate of Flame Propagation: The speed at which a flame travels through a mixture of gases.

Backhand Welding: A gas welding technique wherein the flame is directed opposite to the progress of welding.

Forehand Welding: A gas welding technique wherein the flame is directed toward the progress of welding.

GROUP VI—RESISTANCE WELDING*

A. Welding Processes

Resistance Welding: A pressure welding process wherein the heat is obtained from the resistance to the flow of an electric current.

Resistance Butt Welding: A group of resistance welding processes wherein the weld occurs simultaneously over the entire contact area of the parts being joined.

Flash Butt Welding: A resistance butt welding process wherein the necessary heat is derived from an arc or series of arcs established between the parts being welded prior to the application of the weld consummating pressure which is applied when the heat thus obtained has produced proper welding conditions.

Upset Butt Welding: A resistance welding process wherein the current is applied after the parts to be welded are brought in contact and wherein the heat is derived from resistance to the flow of current.

Spot Welding: A resistance welding process wherein the fusion is confined to a relatively small portion of the area of the lapped parts to be joined by the shape or contour of one or both welding electrodes.

Multiple Spot Welding: A spot welding process wherein two or more separate welds are made simultaneously in parallel.

Poke or Push Welding: A spot welding process wherein pressure is applied manually to one electrode only.

Projection Welding: A resistance welding process wherein localization of heat between two or more surfaces or between the end of one member and surface of another is effected by projections.

Multiple Projection Welding: A projection welding process wherein two or more separate welds are made simultaneously in parallel.

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*NOTE: Definitions of all resistance welding terms shown herein were formulated and approved by the Nomenclature Committee of the Resistance Welder Manufacturers' Association.

Seam Welding: A resistance welding process wherein overlapping or tangent spot welds are made progressively.

Butt Seam Welding: A seam welding process with the pieces positioned edge to edge.

Lap Seam Welding: A seam welding process with the parts to be welded overlapped.

Mash Seam Welding: A seam welding process wherein the overlap is maintained sufficiently small to permit fusion and plastic reduction of the overlap to approximately the thickness of one of the parts being joined.

Series Welding: A resistance welding process wherein two or more welds are made simultaneously by a single welding transformer with the total current passing through every weld.

Hydromatic Welding: A resistance welding process wherein each one of two or more electrodes in sequence goes through a complete welding cycle under the control of a hydraulic sequencing device synchronized with a welding current control device.

Percussive Welding: A resistance welding process wherein a relatively intense discharge of electrical energy and the application of high pressure (usually a hammer-like blow) occur simultaneously or with the electrical discharging occurring very slightly before the application of the pressure or hammer blow.

Pulsation Welding: A spot, projection or seam welding process wherein the welding current is interrupted one or more times without release of pressure or change of location of electrodes.

Stored Energy Welding: A resistance welding process wherein the electrical energy required to produce the weld is accumulated in a suitable storage reservoir, usually at a low rate, prior to its delivery to the weld, usually delivered at a high rate.

Ultra Speed Welding: A resistance welding process wherein two or more welding electrodes are in simultaneous contact with the material to be welded with the welding current commutated successively between the welding electrodes by means of a commutating device in the secondary welding current circuit.

B. Welds

Spot Weld: A weld made by a spot welding process. See Spot Welding and Figure 46.

Projection Weld: A weld made by a projection welding process. See Projection Welding and Figure 47.

Butt Seam Weld: A weld made by a butt seam welding process. See Butt Seam Welding and Figure 48.

Lap Seam Weld: A weld made by a lap seam welding process. See Lap Seam Welding and Figure 49.

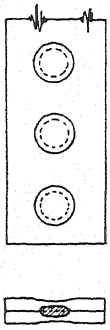


Fig. 46—Spot Weld

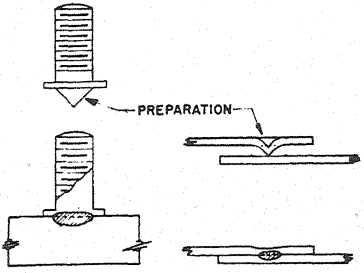


Fig. 47—Projection Welds

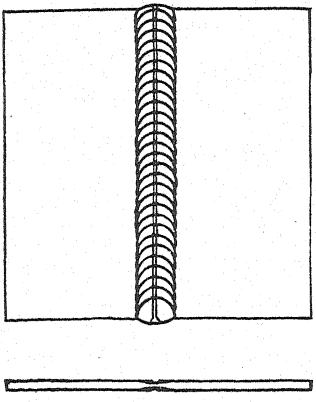


Fig. 48—Butt Seam Weld

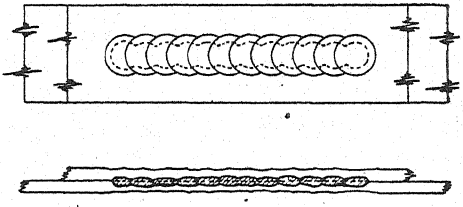


Fig. 49—Lap Seam Weld

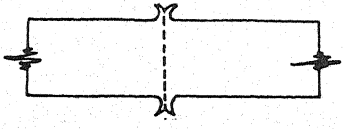


Fig. 50—Flash Butt Weld

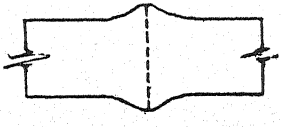


Fig. 51—Upset Butt Weld

Flash Butt Weld: A weld made by a flash butt welding process. See Flash Butt Welding and Figure 50.

Upset Butt Weld: A weld made by an upset butt welding process. See Upset Butt Welding and Figure 51.

C. Materials and Equipment

Resistance Welder: A resistance welding machine. (The term "welder" has sometimes been used to denote an operator of welding equipment, for which the term Welding Operator is greatly to be preferred.)

Electrode: The part or parts of a resistance welding machine through which the welding current and pressure are applied directly to the work.

Electrode Holder: A device used for mechanically holding the electrode.

Auxiliary Lift: A device or means to permit manual or power operation of the top electrode holder or arm beyond and independent of its normal welding stroke.

Air Cushion: A pneumatic pressure device incorporated in the air operating mechanism of the resistance welder to provide a deceleration of a mechanical motion, which may or may not be adjustable.

Speed Control Valve: A combination check and needle valve restricting the flow of air or liquid in one direction and affording unrestricted passage to the air or liquid in the opposite direction.

D. Welding Details

Squeeze Period: The time interval in a resistance welding process between the application of pressure and the application of welding current.

Heat Time: The time of duration of each current impulse in pulsation welding.

Cool Time: The period of time between the successive applications of current impulses in pulsation welding.

Weld Time: The interval during which current is allowed to flow through the work during the performance of one weld. In pulsation welding, the weld period includes the "cool" time intervals.

Hold Time: The time that pressure is maintained at the electrodes after the cessation of the welding current.

Off-Time: The time in the resistance welding process that one or both electrodes are separated from the parts welded.

Weld Period: The time required to go through one complete cycle of a welding operation.

Welding Pressure: External force applied in the pressure welding processes to control the current density throughout the weld, or effects of heat or both.

Flash: Metal and oxide expelled from a joint made by a resistance-welding process.

Non-Beat: A provision in the operating controls of a welding machine to insure completion of the operating cycle after the cycle has been initiated.

Throat Depth: The distance from the center line of the electrodes to the first obstruction limiting the insertion of the work, usually measured in a horizontal plane.

Throat Opening: The variable dimension between the inner surfaces of current carrying members (arms, knees, or platens, etc.) taken at right angle to the measurement of throat depth.

GROUP VII—BRAZING

A. Welding Processes

Brazing: A group of welding processes wherein the filler metal is a non-ferrous metal or alloy whose melting point is higher than 1000°F. but lower than that of the metals or alloys to be joined.

Gas Brazing: A brazing process wherein the heat is obtained from a gas flame.

Electric Brazing: A group of brazing processes wherein the heat is obtained from electric current.

Arc Brazing: An electric brazing process wherein the heat is obtained from an electric arc, formed between the base metal and an electrode, or between two electrodes.

Induction Brazing: An electric brazing process wherein the heat is obtained from induced current.

Resistance Brazing: An electric brazing process wherein the heat is obtained from the resistance to the flow of an electric current.

Furnace Brazing: A brazing process wherein the heat is obtained from a furnace.

Dip Brazing: A group of brazing processes wherein the heat is obtained from a bath of molten metal or chemical; the filler metal may or may not be obtained from the bath.

Metal Dip Brazing: A dip brazing process wherein the filler metal is obtained from the molten metal bath.

Chemical Dip Brazing: A dip brazing process wherein the filler metal is added to the joint before immersion in a bath of molten chemicals.

GROUP VIII—THERMIT WELDING

A. Welding Processes

Thermit Welding: A non-pressure (fusion) welding process wherein the heat is obtained from liquid steel produced by a thermit reaction, and the filler metal is supplied by the steel produced in this reaction.

Pressure Thermit Welding: A pressure welding process wherein the heat is obtained from the liquid products of a thermit reaction.

B. Materials and Equipment

Thermit Mould: A mould formed around the parts to be welded, to receive the molten metal.

Thermit Crucible: The vessel in which the thermit reaction takes place.

Plain Thermit: A mixture of iron oxide and finely divided aluminum.

Thermit Mixture: A mixture of plain thermit, alloying metals and mild steel.

Cast Iron Thermit: A thermit mixture containing additions of ferrosilicon and mild steel.

Forging Thermit: A thermit mixture with the addition of carbon, manganese, nickel and mild steel.

C. Welding Details

Thermit Reaction: A chemical reaction between iron oxide and aluminum which produces a highly superheated liquid iron and aluminum oxide slag.

Wax Pattern: Wax moulded around the parts to be welded by the thermit welding process to the form desired for the completed weld.

Heating Gate: The opening in a thermit mould through which the parts to be welded are preheated.

Collar: The reinforcing metal of a non-pressure thermit weld.

GROUP IX—FORGE WELDING

A. Welding Processes

Forge Welding (Blacksmith, Roll, Hammer): A group of pressure welding processes wherein the parts to be welded are brought to suitable temperature by means of external heating and the weld is consummated by pressure or blows.

GROUP X—ARC AND OXYGEN CUTTING

A. Cutting Processes

Oxygen Cutting: A process of severing ferrous metals by means of the chemical action of oxygen on elements in the base metal at elevated temperatures.

Oxygen Grooving: A process of forming a groove in the surface of ferrous metals by means of the chemical action of oxygen on elements in the base metal at elevated temperatures.

Oxygen Machining: A process of shaping ferrous metals by oxygen cutting or oxygen grooving.

Carbon Arc Cutting: The process of severing metals by melting with the heat of the carbon arc.

Metal Arc Cutting: The process of severing metals by melting with the heat of the metal arc.

B. Cutting Details*

Kerf: The space from which the metal has been removed by a cutting process.

Drag: The horizontal distance between the point of entrance and the point of exit of a cutting oxygen stream.

Cutting Torch or Blowpipe: A device used in gas cutting for controlling the gases used for preheating and the oxygen for severing the metal.

Cutting Tip: A gas torch tip especially adapted for cutting.

Cutting Attachment: A device which is attached to a welding torch to convert it to a cutting torch.

GROUP XI—TESTING AND INSPECTION

A. General

All-Weld-Metal Test Specimen: A test specimen wherein the portion being tested is composed wholly of weld metal.

Base Metal Test Specimen: A test specimen composed wholly of base metal.

Free Bend Test: A bending test wherein the specimen is bent without constraint of a jig.

Guided Bend Test: A bending test wherein the specimen is bent to a definite shape by means of a jig.

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*NOTE: Definitions of Mixing Chamber, Cylinder and Manifold, which apply to oxygen cutting as well as to gas welding, are given in Group V-B, page 1544.

B. Radiographic Inspection

Radiography: The use of radiant energy in the form of X-rays or gamma-rays for the non-destructive examination of opaque objects, which yields a graphical record of their soundness on sensitized films.

X-Rays: A form of radiant energy derived from the bombardment of a material by electrons in a vacuum at a high voltage, the wave length of the rays being between 10^{-11} and 10^{-8} cm.

Gamma-Rays: A form of radiant energy derived from the atomic transformation of radioactive matter, the wave length of the rays being about 10^{-11} cm.

Radiograph: A shadow picture produced by passing X-rays or gamma-rays through an object and recording the variations in the intensity of the emergent rays on a suitable sensitized film.

Exograph: A radiograph produced by X-rays.

Gamma-graph: A radiograph produced by gamma-rays.

Cassette: A light-proof holder to contain the sensitized film during exposure to X-rays or gamma-rays.

Intensifying Screen: A layer of a material which is placed in contact with the film for the purpose of increasing the effect of the radiation on the film.

Filter: A sheet or strips on edge (which may be oscillated) of absorptive material placed between the film and the object being radiographed, to reduce the effect of secondary and scattered radiation.

Penetrameter: A strip of metal of a thickness equal to a specified percentage of the thickness of the material under examination, and containing holes with diameters bearing a specified relation to the thickness of the strip, used to check the radiographic technique.

Focus-film distance: The distance in inches between the focal spot of the X-ray or the radium capsule and the film.

Halation: The spread of the image in regions of intense exposure due to photochemical action in the film or intensifying screens or to fluorescent light scatter, but not to scattered radiographic rays.

CHAPTER 43

WELDING SYMBOLS AND INSTRUCTIONS FOR THEIR USE*

Welding cannot take its proper place as an engineering tool unless means are provided for conveying the information from the designer to the workmen. Unimportant work may be directed by means of inadequate information on drawings, but when structures, the failure of which would endanger life and property, are to be welded, simple and specific means must be used to convey the ideas of the designer to the shop. Such practices as writing "To be welded throughout" or "To be completely welded" on the bottom of a drawing, in effect, transfer the design of all attachments and connections from the designer to the welding operator, who cannot be expected to know what strength is necessary. This practice in addition to being highly dangerous is also costly, for certain shops, in their desire to be safe, use much more welding than is necessary.

These symbols provide the means of placing complete welding information on drawings. Even though the legends, numerical data and the instructions involve a considerable mass of material, nevertheless the successful use of the scheme depends so little on the memory that hardly more than one reading of the instructions is necessary to obtain a working understanding of the system. In practice many companies will probably need only a few of the symbols, and if they desire, can make up their own legends to suit themselves, selecting such parts of the scheme as fit their needs and neglecting the others. If this is done universally, we shall all be speaking the same language even though some use but a few of the symbols contained herein.

In these symbols, the general principle of having the most usual form of any weld require a minimum of numerical data, has been followed. When a weld departs from the user's standard, supplementary data are necessary. This makes the user's standards a part of the symbols system, and means that the exact interpretation of the symbols will vary slightly among the different users.

It will be seen from Fig. 1 that the arc and gas welding symbols are ideographic; that is, they are picture-writing symbols; they show graphically the type of weld required. The individual basic symbols become the building blocks with which compound symbols to indicate complicated welded joints composed of many welds, can be constructed. Every weld in the joint must be shown.

The use of the words "far side" and "near side," etc. in the past has led to confusion because it was often not clear as to whether "side" referred to member, joint or weld. Also, when joints are shown in section, all welds are equally distant from the reader and the words near and far are factually improper. In the present symbol system the joint is the basis of reference. Any joint whose welding is indicated by a symbol will always have an "arrow side" and an "other side." Accordingly, the words "arrow side," "other side" and "both sides" are used herein to locate the weld with re-

* Standard of the AMERICAN WELDING SOCIETY.

spect to the *joint*. Since the words near and far have been used in the past and in some cases do have significance, they have been retained in a subordinate position.

In Fig. 2 are shown the various fundamental kinds of joints and the line of the joint is indicated thereon. The interpretation of the arrow side and other side is apparent.

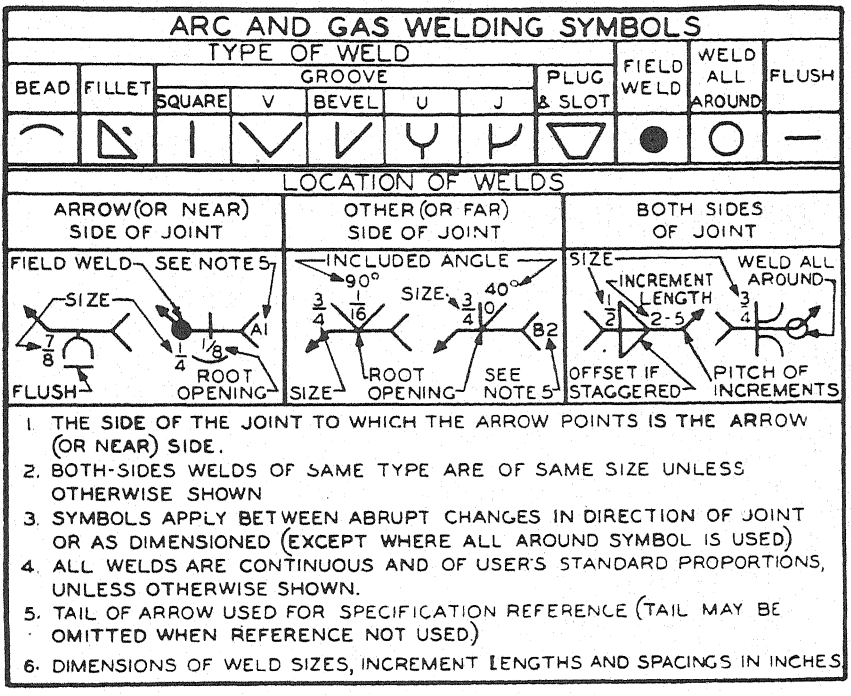


Fig. 1—Legend for Use on Drawings Specifying Arc and Gas Welding

Under previous symbols systems it has been possible to show the welding on hidden members. Theoretically under the new system it is necessary to make a detail sketch to show the welding of any hidden member. Actually, however, such is not the case. The welding on hidden members can be covered as shown in Fig. 3 when welding of the hidden member is the same as that of the visible member. The fact that there are two members must be covered by both the drawing and the bill of material. If the welding on the hidden member is different from that of the visible member, obviously specific information for the welding of both must be given.

The distinction between the symbols for the V- and bevel-groove welds and the U- and J-groove welds is not great. The draftsman should take sufficient care in the making of these particular symbols so that they do not become confused with each other.

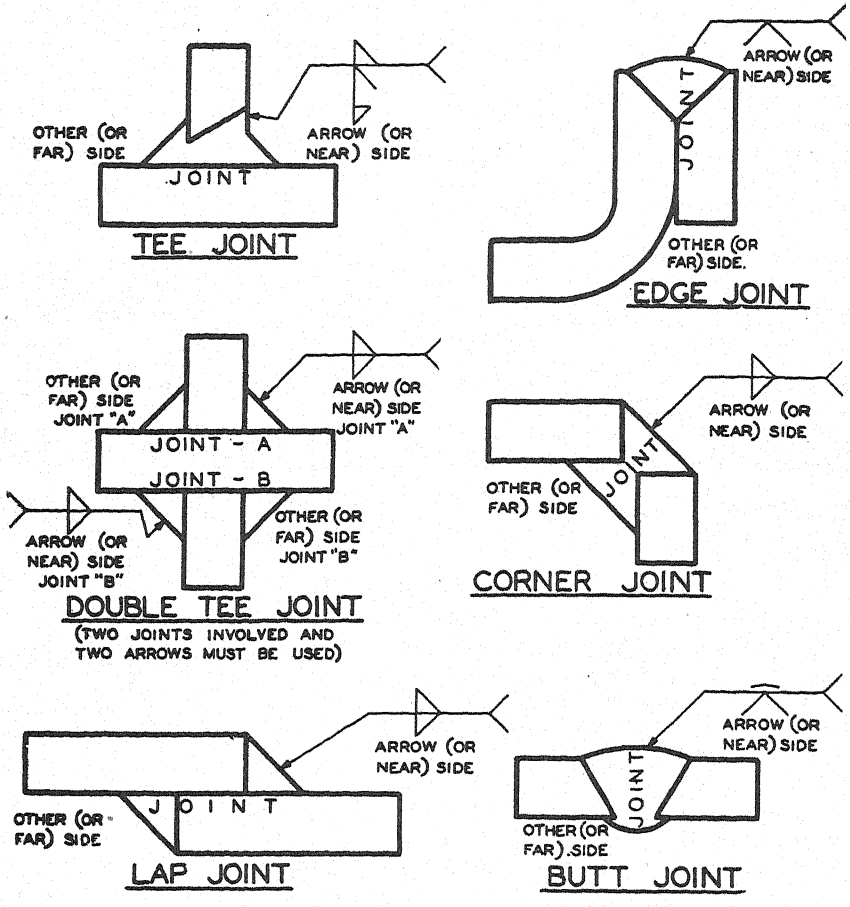


Fig 2—Location of Line of Joint in the Various Fundamental Types of Joints

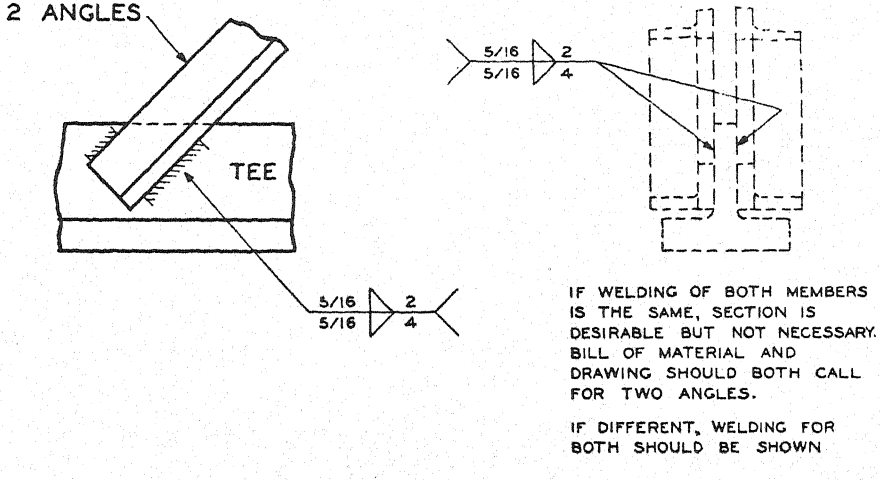


Fig. 3—Method of Calling for Welding of Hidden Members

The field weld symbol is the black dot used by the structural industry to indicate field riveting. In the case of work actually erected in the field, just what constitutes field welding is simple. In the case of work done in the shop, yet done in the actual erection of the final product, the case is not so simple. An illustration of this obtains when work is done in the shop on an assembly line, such as is used in the automobile or car building industries. In this case, the individual user must decide for himself whether such erection welding is shop welding or field welding.

Appropriate finish marks have been found to be necessary; however, recommendations as to what finish marks shall be used are not strictly within the province of the Committee. As soon as the American Standards Association has definitely decided upon a system of finish symbols, it will be desirable for all concerned to adopt this system. In the meantime, however, a suggestion with regard to finish marks is made. It will be

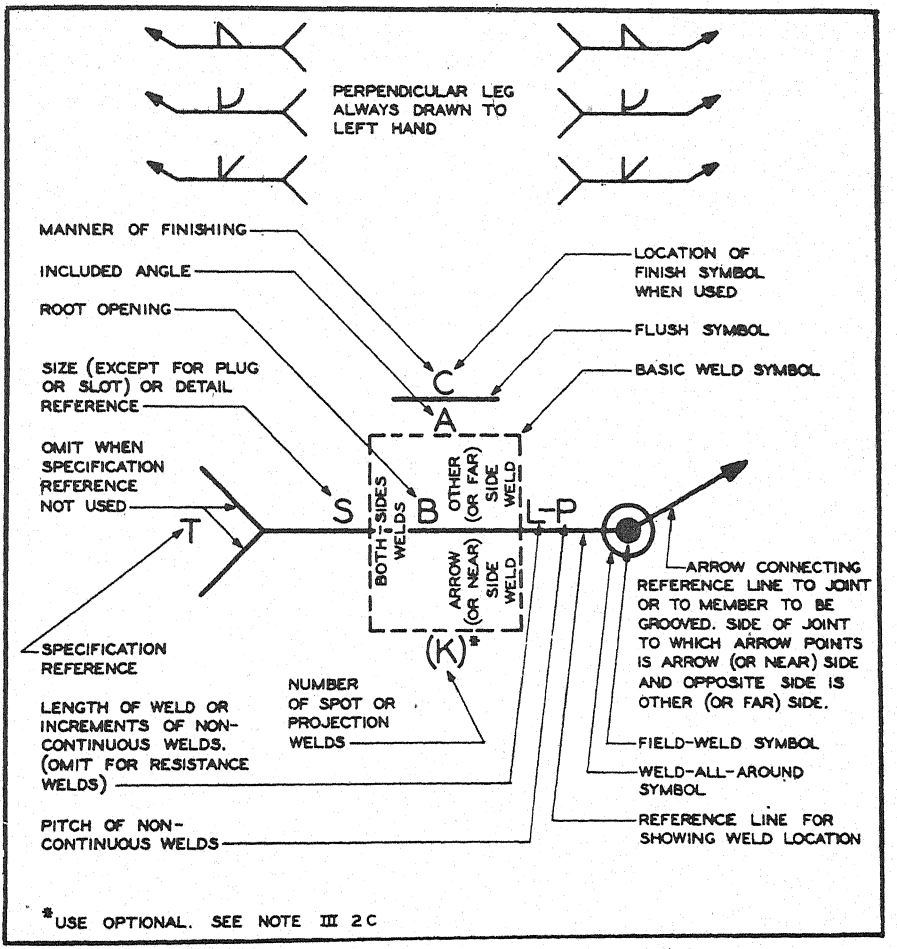


Fig. 4—Standard Locations of Information on Welding Symbols

noted in Section IV of the Instructions that these finish marks merely suggest the means of finishing; that is, whether chipping, grinding or machining be used, and not the degree; they do not say whether a weld is to be rough or finish machined, rough or smooth ground, etc. Any such fine distinction must be made in the user's standard manner until such time as a national standard is established.

The location of the Symbols, numerical and other data on the reference line always has definite significance. This is depicted in Fig. 4 in which the standard manner of placing information on the symbols is shown diagrammatically. Particular attention should be paid to the fact that the perpendicular leg of the weld should always be to the left as shown at the top of Fig. 4.

The proper and improper use of the arrows to designate the member to be grooved is shown in Fig. 5.

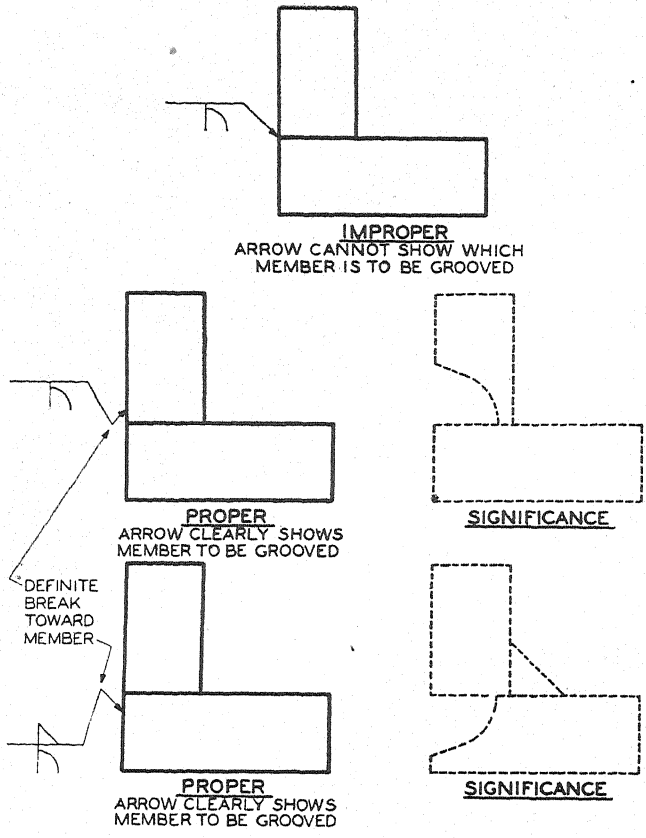
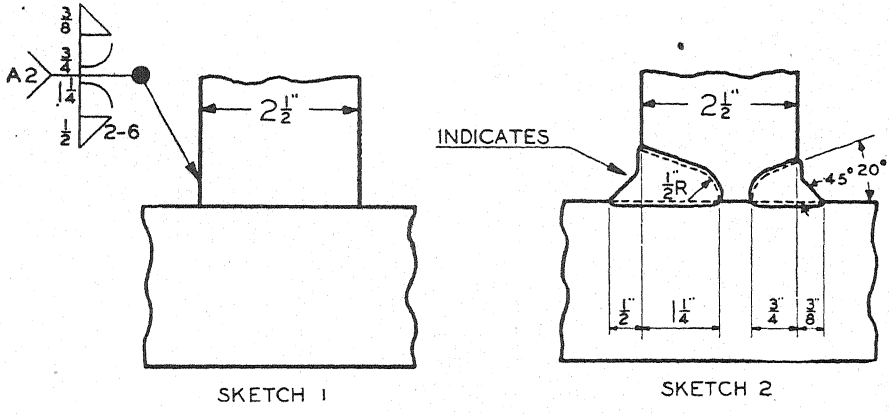


Fig. 5—Use of Arrows in Section or End View to Indicate Which Member Is to Be Grooved, When Welds Are Not Shown

A new feature incorporated in this revision is the use of the tail of the reference line for designating the welding specifications to be used in the making of the weld. If a welding operator knows the size and type of weld, he has only part of the information necessary for the making of that weld. The process, type and make of filler metal that is to be used, whether or not peening or chipping are required, and other pertinent data must be known before he can start the work. The specification to be placed in the tail of the reference line at present will have to be handled by each individual company which will set up its own requirement in any manner it sees fit, and it is hoped that in time a national set of standards will be prepared to coordinate the various specification processes in use. Steps in that direction are now under consideration. Such matters as stress-relief annealing, and final cleaning of the product cannot be referred to on the symbol because such treatment is applied to the product as a whole and not to a particular weld.

The symbols, together with the specification references, provide a shorthand system whereby a tremendous volume of information may be accurately indicated with a few lines and a minimum amount of numerical data. This is illustrated in Fig. 6, where the words necessary to convey the information given by the symbol would make a very long paragraph.

The use of the symbols on a machinery drawing is shown in Fig. 7, and on a structural drawing in Fig. 8. In these views examples of the use of the specification references are given.



Interpretation of Symbol:

Double-fillet-welded, partially-grooved, double-J, tee-joint with incomplete penetration. Type of joint shown by drawing.) Grooves of standard proportions (which are, 1/2 in. R, 20° included angle, edges in contact before welding) 3/4 in. deep for other (or far) side weld and 1 1/4 in. deep for arrow (or near) side weld. 3/8 in. continuous other (or far) side fillet weld and 1/2 in. intermittent arrow (or near) side fillet weld with increments 2 in. long, spaced 6 in. center-to-center. All fillets standard 45° fillets. All welding done in field in accordance with welding specification number A2 (which requires that weld be made by manual D.C. shielded metal-arc process using high-grade, covered, mild steel electrode; that root be unchipped and welds unpeened but that joint be preheated before welding).

Fig. 6—Comparison Between Symbolic and Verbal Methods of Conveying Welding Information

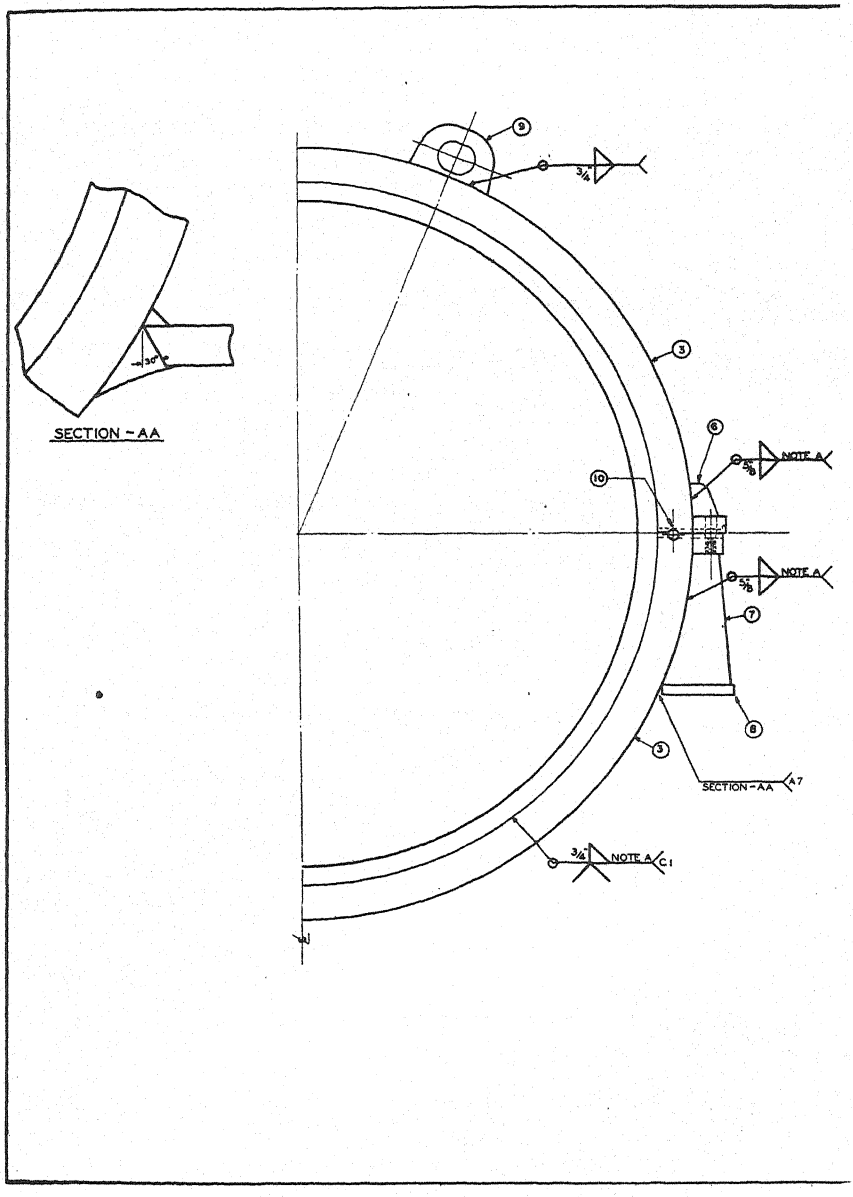
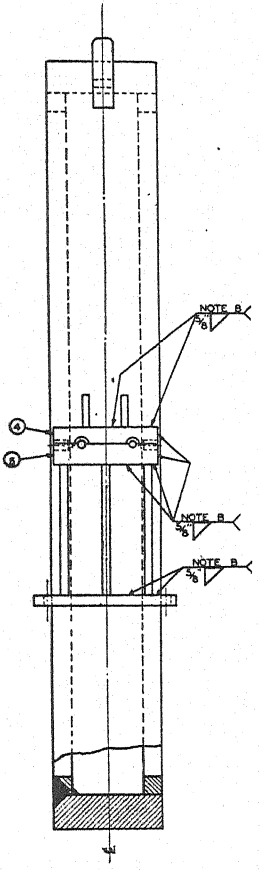


Fig. 7—Typical Machinery



NOTES:

A. THESE WELDING SYMBOLS APPLY TO THE JOINTS OF ALL MEMBERS OF THE SAME IDENTIFICATION.

B. WELDING SYMBOLS SHOWN HERE APPLY TO BOTH SIDES OF CENTER LINE.

ARC AND GAS WELDING SYMBOLS

TYPE OF WELD: BEAD | FILLET | GROOVE: SQUARE, V, BEVEL, U, J | PLUG & SLOT | FIELD WELD | WELD ALL AROUND | FLUSH

LOCATION OF WELDS: ARROW (OR NEAR) SIDE OF JOINT | OTHER (OR FAR) SIDE OF JOINT | BOTH SIDES OF JOINT

FIELD WELD · SEE NOTE 5 · SIZE · FLUSH · ROOT OPENING · INCLUDED ANGLE ~90° · ~40° · SIZE · ROOT OPENING · SEE NOTE 5 · SIZE · INCREMENT LENGTH · WELD ALL AROUND · OFFSET IF STAGGERED · PITCH OF INCREMENTS

1. THE SIDE OF THE JOINT TO WHICH THE ARROW POINTS IS THE ARROW (OR NEAR) SIDE.
2. BOTH SIDES WELDS OF SAME TYPE ARE OF SAME SIZE UNLESS OTHERWISE SHOWN.
3. SYMBOLS APPLY BETWEEN ABRUPT CHANGES IN DIRECTION OF JOINT OR AS DIMENSIONED (EXCEPT WHERE ALL AROUND SYMBOL IS USED)
4. ALL WELDS ARE CONTINUOUS AND OF USER'S STANDARD PROPORTIONS, UNLESS OTHERWISE SHOWN.
5. TAIL OF ARROW USED FOR SPECIFICATION REFERENCE (TAIL MAY BE OMITTED WHEN REFERENCE NOT USED)
6. DIMENSIONS OF WELD SIZES, INCREMENT LENGTHS AND SPACINGS IN INCHES

WELDING NOTES

1. UNLESS OTHERWISE DESIGNATED ALL WELDS TO BE MADE IN ACCORDANCE WITH SPECIFICATION NO. A1 AS LISTED BELOW.	
2. FILLER METAL (BRAND OR NAME)	
3. FLUX (OTHER THAN ON RODS)	NONE
4. PEENING	NONE
5. PREHEATING	NONE
6. PRECLEANING	NONE
7. POSITION OF WELDING	FLAT ONLY
8. SEQUENCE	AS REQUIRED
9. STRESS-RELIEF ANNEALING	NONE
10. NON-DESTRUCTIVE EXAMINATION	NONE
11. SIZE OF ALL UNDIMENSIONED FILLETS	INCHES

SPECIFICATIONS FOR MAKING INDIVIDUAL WELDS

SPECIFICATION NUMBER	PROCESS	FILLER METAL	CHIPPING OF ROOT	PEENING	PREHEAT
A 1	SHIELDED METAL-ARC MANUAL, D.C.	GRADE EA	NONE	NONE	NONE
C 1	SHIELDED METAL-ARC AUTOMATIC, D.C.	GRADE EA	NONE	NONE	NONE
A 7	SHIELDED METAL-ARC MANUAL, D.C.	GRADE EA	YES	YES	NONE

MARK	NO.	NAME	MATERIAL	RELATED DRAWINGS

LIST OF PARTS

FOR OTHER DRAWINGS SEE FOLLOWING NUMBERS

REVISIONS

FINISH MARKS

C – CHIP
G – GRIND
M – MACHINE

TYPICAL MACHINERY DRAWING SHOWING USE OF SYMBOLS

19

DRAWN BY
CHECKED BY
TRACED BY
TRACING CHKD. BY

SCALE

Drawing Showing Use of Symbols

In Fig. 9 are shown the resistance welding symbols. There are many similarities between the resistance and the arc welding symbols and three principal differences. The resistance symbols are only partially ideographic. The arc symbols designate the size of the weld, whereas the resistance welding symbols call for the strength of the required weld. This difference is necessary because in spot, projection and seam welding, the weld is inaccessible and therefore cannot be gaged as in fusion welding. Except for the case of projection welding where arrow (or near) and other (or far) refer to the member to be embossed, the resistance welding symbols have no arrow side and other side significance. Supplementary symbols such as those for "finish" have their usual arrow side and other side significance when used on resistance welding symbols.

The Committee wishes to make two points very clear. First—that the individual company may use just as much or as little of the system as it sees fit, and second—that the system may be used in any of the various ways listed below:

(*a*) All symbol legends and explanatory matter may be issued as company standards on sheets separate from the drawing in question; that is, the draftsman may have explanatory supplementary sheets as well as machinists, welding operators, inspectors, etc.

(*b*) Legends and specification references may be placed on the drawing so that the latter is completely self-explanatory.

(*c*) In either of the above cases, the welds may be drawn in sections and the symbol give only that information that is not obvious, such as size of weld, length of increment, etc.

(*d*) In either of the cases (*a*) and (*b*) above, the welds may not be drawn in section and complete information conveyed by symbols.

(*e*) The symbol legends, specification references and standard notes may be printed on the tracing or may be placed on tracings or prints by rubber stamps or any other means.

INSTRUCTIONS FOR USE OF WELDING SYMBOLS

I General

(*a*) Do not use the word "weld" as a symbol on drawings.

(*b*) Symbols may or may not be made freehand as desired.

(*c*) Inch, degree and pound marks may or may not be used as desired.

(*d*) The symbol may be used without specification references or tails to designate the most commonly used specification when the following note appears on the drawing:
"Unless otherwise designated, all welds to be made in accordance with welding specification No. —."

(*e*) When specification references are used, place in tail, thus:



(*f*) Symbols apply between abrupt changes in direction of joint or to extent of hatching or dimension lines (except where all-around symbol is used). See IV *d* and *e*.

(*g*) Faces of welds assumed to have user's standard contours unless otherwise indicated.

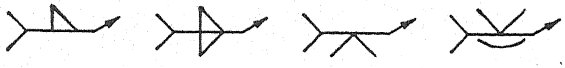
(*h*) Faces of welds assumed not to be finished other than cleaned unless otherwise indicated.

(*i*) All except plug, spot, and projection welds assumed continuous unless otherwise indicated.

II *Arc and Gas Welds*

1. General

(*a*) Do not put symbol directly on lines of drawing; place symbol on reference line and connect latter to joint with arrow, thus:



(*b*) For welds on arrow (or near) side of joint show symbol on near side of reference lines, face toward reader, thus:



(*c*) For welds on other (or far) side show symbol on far side of reference line, face away from reader, thus:



(*d*) For welds on both sides of joint show symbols on both sides of reference line, faces toward and away from reader, thus:



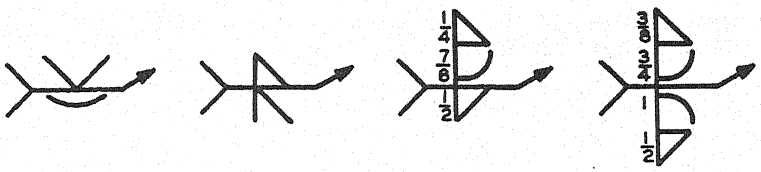
(*e*) Where the part shown is but one of a series of practically identical parts (see the vertical ribs in Figure 7), the applicability of the symbols to the concealed parts shall be in accordance with the user's standard drawing practices with regard to dimensioning and part-numbering such parts.

(*f*) Where one member only is to be grooved, show arrow pointing unmistakably to that member. (See Figure 5.)

(*g*) Read symbols from bottom and right-hand side of drawing in the usual manner and place numerical data on vertical reference lines so that reader will be properly oriented, thus:



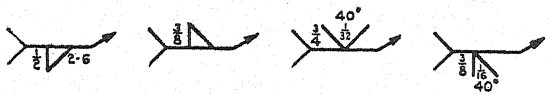
(*h*) Show symbol for each weld in joints composed of more than one weld, thus:



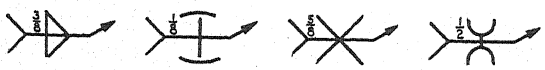
(Give numerical data in proper location with regard to each symbol.)

(*i*) In complicated joints requiring large compound symbols two separate sets of symbols may be used if desired.

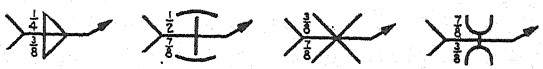
(*j*) Show dimensions of weld on same side of reference line as symbol, thus:



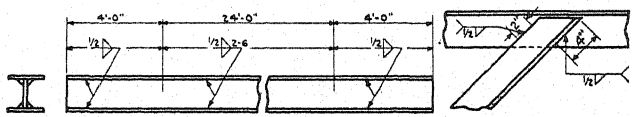
(*k*) Show dimensions of one weld only when welds on both sides of the joint are of the same type and size, thus: (If size of undimensioned fillets is governed by a note on the drawing, all weld sizes different from that covered in the note must be given.)



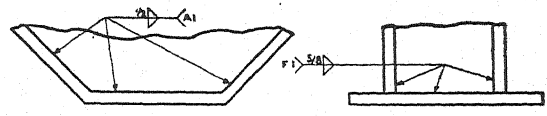
(*l*) Show dimensions for welds on both sides of the joint, when the arrow-side and other-side welds are different, thus:



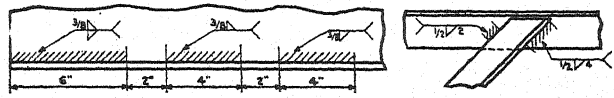
(*m*) Indicate specific lengths of welds in conjunction with dimension lines, thus:



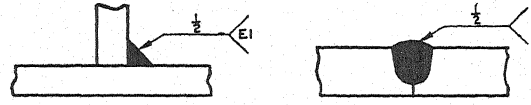
(*n*) Show the welding between abrupt changes in the direction of the weld thus (except when all-around symbol is used; see IV *d* and *e*):



(*o*) When it is desired to show extent of welds by hatching, use one type of hatching with definite end lines, thus:



(*p*) If actual outlines of welds are drawn in section or end elevation, basic symbol is not necessary to show type and location; size or other numerical details only need to be given, thus:

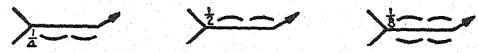


(*q*) Show fillet, bevel- and J-groove weld symbols with perpendicular leg always to the left hand, thus:

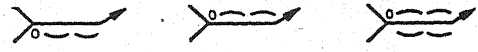


2. Bead Welds

(*a*) Show bead welds used in building up surfaces (size is minimum height of pad) thus:

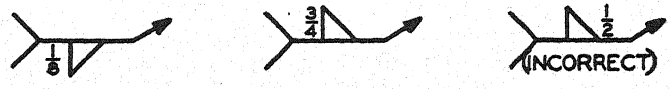


(*b*) When a small but no specific minimum height of pad is desired, show thus:



3. Fillet Welds

(*a*) Show size of fillet weld to the left of the perpendicular leg, thus:



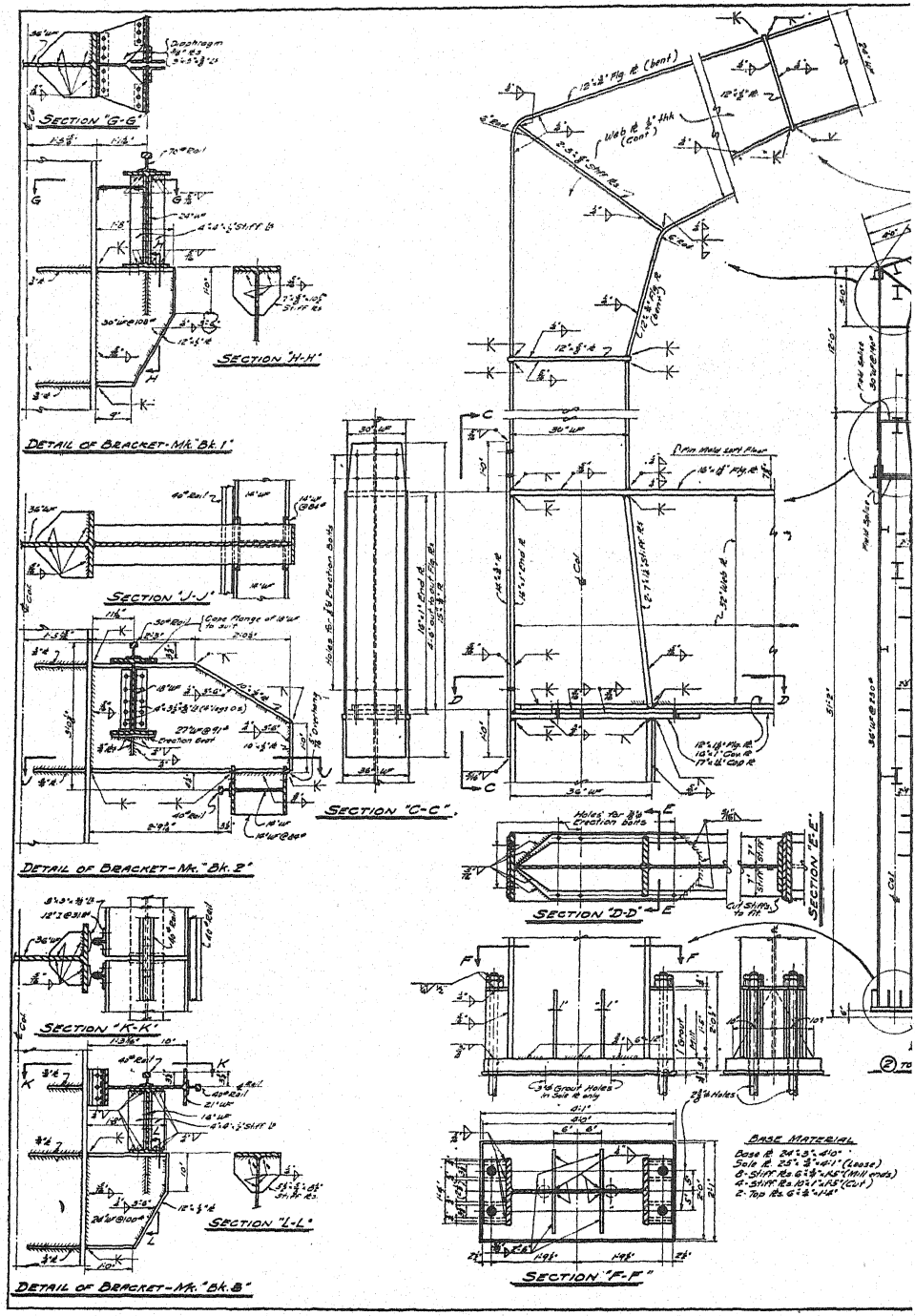
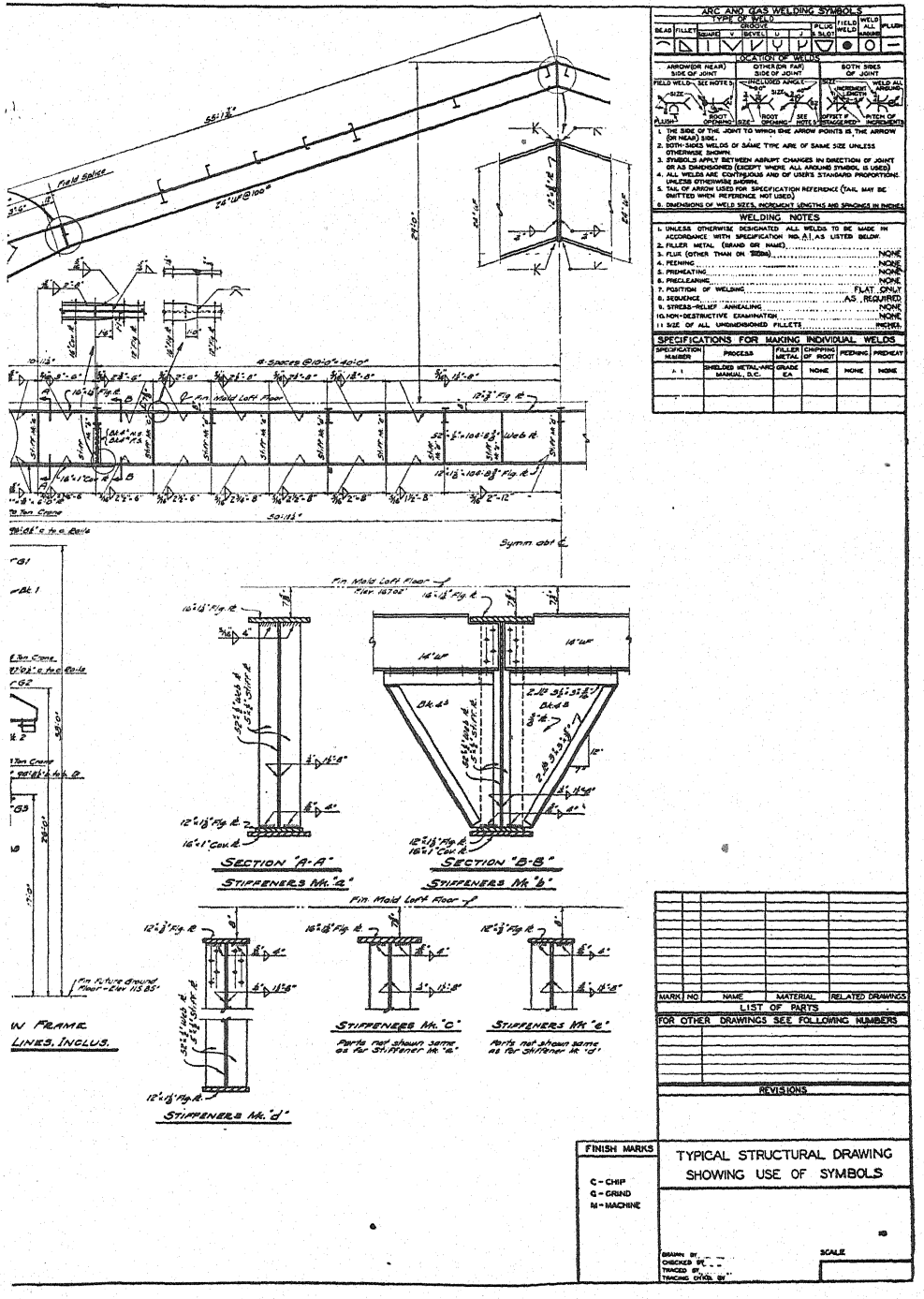


Fig. 8—Typical Structural



Drawing Showing Use of Symbols

(*b*) Show specific length of fillet weld or increment after size so that data read from left to right, thus:

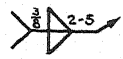


(*c*) Show center-to-center pitch of increments of intermittent fillet welds after increment length so that data read from left to right, thus:

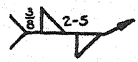


(*d*) Use separate symbol for each weld when intermittent and continuous fillet welds are used in combination.

(*e*) Show two intermittent fillet welds with increments opposite each other (chain) thus:

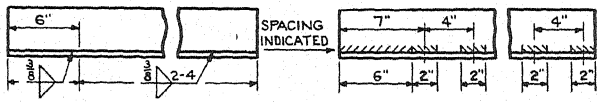


(*f*) Show two intermittent fillet welds with increments not opposite each other (staggered) thus:



(*g*) Measure pitch of intermittent fillet welds between centers of increments on one side of member.

(*h*) Increments and not spaces assumed to be at ends of all intermittent welds and overall length dimensions govern to ends of those increments, thus:



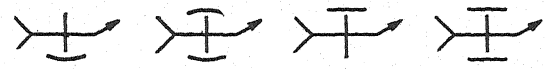
(*i*) Faces of fillet welds assumed to be at 45° from legs unless otherwise indicated.

(*j*) When the face of a fillet weld is to be at any other angle than 45°, two dimensions are necessary to fully designate the size of the weld. Place these dimensions in parentheses so that the two dimensional size data will be a single entity and will not be confused with length of increment and spacing data. Show on drawings positions of legs relative to members.



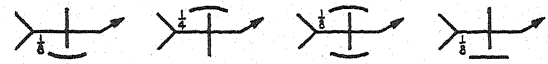
4. Groove Welds

(*a*) Show side from which square-groove weld is made by bead or flush symbols, thus (see III, 4*a;* IV, *h;* and IV, *j* and *k*):

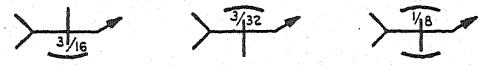


(*b*) Penetration of square-groove welds assumed to be complete unless otherwise indicated.

(*c*) Show size of square-groove welds (depth of penetration) when penetration is less than complete, thus:

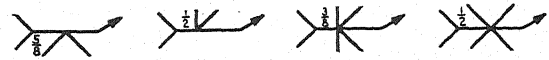


(*d*) Show root opening of open, square-groove welds inside symbol, thus:



(*e*) Total depth of V- and bevel-grooves before welding assumed to be equal to thickness of member unless otherwise indicated.

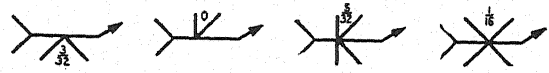
(*f*) Show size of V- and bevel-groove welds (depth of single groove before welding) when grooving is less than complete, thus:



(*g*) Penetration of V- and bevel-groove welds assumed complete, unless with usual welding processes, depth of grooving is such that complete penetration is not possible, when depth of penetration is assumed to be depth of groove plus normal penetration. When using welding processes giving abnormal penetration, give information on latter by detail or note (see IV, *o*).

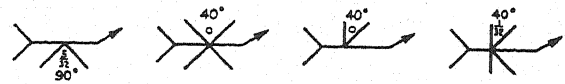
(*h*) Root opening of V- and bevel-groove welds assumed to be user's standard unless otherwise indicated.

(*i*) Show root openings of V- and bevel-groove welds when not user's standard, inside symbol, thus:



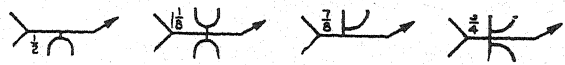
(*j*) Included angle of V- and bevel-groove welds assumed to be user's standard unless otherwise indicated.

(*k*) Show included angle of V- and bevel-groove welds when not user's standard, inside symbol, thus:

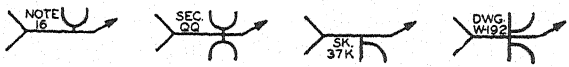


(*l*) Proportions of U- and J-groove welds assumed to be user's standard unless otherwise indicated.

(*m*) Show size of U- and J-groove welds (depth of single groove before welding) having user's standard proportions but incomplete penetration, thus:



(*n*) When proportions of U- and J-groove welds are not user's standard, show weld by detail or reference drawing and use reference symbol, thus (see IV, *o*):



(*o*) Show welding done from root side of single-groove welds with bead weld symbol, thus:



5. Plug and Slot Welds

(*a*) Show size of plug and slot welds (root opening and root length), thus:



(Root opening equals root length for plug welds.)

(*b*) Included angle of bevel of plug and slot welds assumed to be user's standard unless otherwise indicated.

(*c*) Show included angle of bevel of plug and slot welds when not user's standard, thus:



(*d*) Show pitch of plug and slot welds in row, thus:



(*e*) Show fillet welded holes and slots with proper fillet weld symbols and not with plug weld symbols.

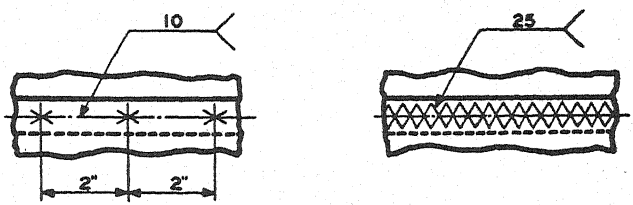
III Resistance Welds

1. General

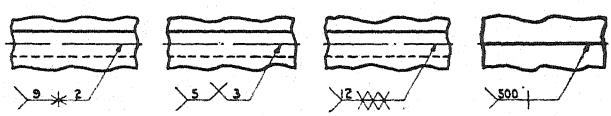
(*a*) Center resistance welding symbols for spot and seam welds on reference line because these symbols have no arrow side or other side (near and far side) significance; (see Figure 9 and also refer to IV *m*) but do not center projection welding symbols because the latter have such significance.

(*b*) Designate resistance welds by strength rather than size (because of impracticability of determining latter).

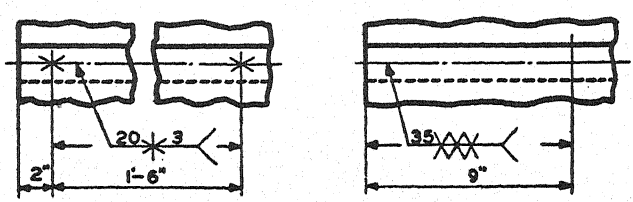
(*c*) Spot and seam weld symbols may be used directly on drawings, thus; but projection weld symbols should not:



(*d*) When not used on lines of drawing, connect reference line to center line of weld or rows of welds with arrow, thus:



(*e*) Show welds of extent less than between abrupt changes in direction of joint, thus:



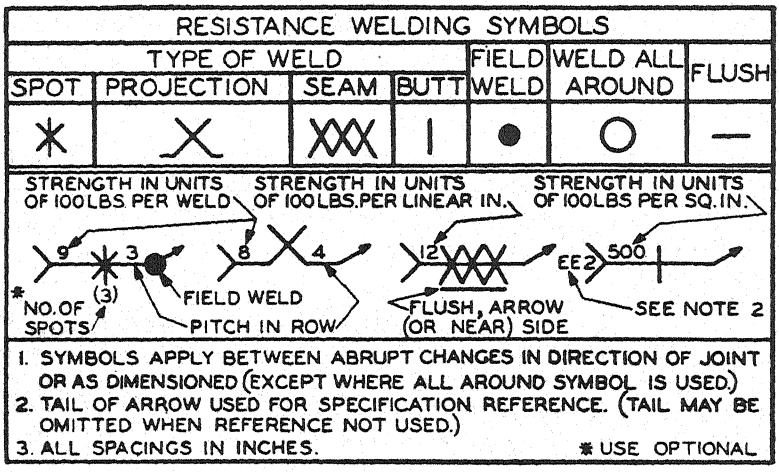
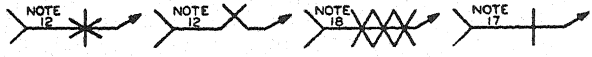


Fig. 9—Legend for Use on Drawings Specifying Resistance Welding

(*f*) When tension, impact, fatigue or other properties are required, use reference symbol, thus (see IV, *o*):



2. Spot and Projection Welds

(*a*) Show strength of spot and projection welds in single shear in units of 100 pounds per weld, thus:



(*b*) Show strength and center-to-center spacing of spot and projection welds in row, thus:



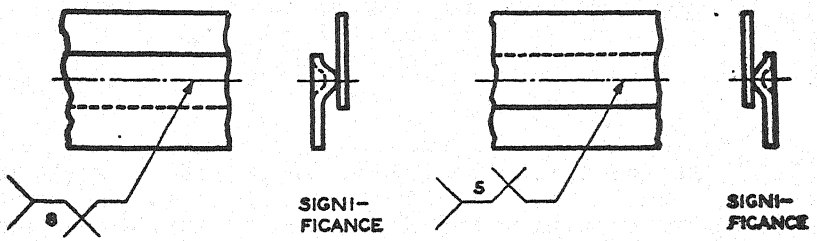
(*c*) When a definite number of spot or projection welds is desired in a certain joint or connection, show that number by a number in parentheses below the symbol, thus:



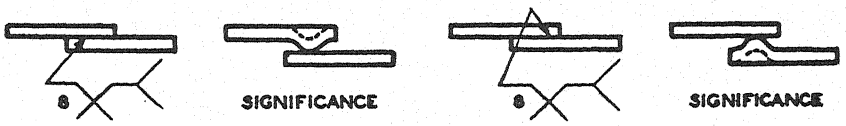
(NOTE: If specific number of spots of a certain strength is called for and spacing omitted, strength of spots can be seriously affected by decrease in spacing. Designers should be sure that when calling for number of spots only, the strength of the connection will not be jeopardized by decreased strength of spots due to variation in spacing.)

(*d*) Proportions of projections assumed given on drawing.

(*e*) In a projection welded joint parallel, or nearly so, to the plane of the paper, show whether the arrow (or near) side or other (or far) side member is to be embossed by placing the projection weld symbol on the arrow (or near) or the other (or far) side of the reference line, thus:



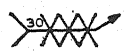
(*f*) In a projection welded joint shown in section or end view, show which member is to be embossed by pointing arrow to that member, thus:



3. Seam Welds

(*a*) Seam welds assumed to be of overlapping or tangent spots. If any spacing exists between spots, welds considered a series of spot welds, and spot symbol should be used.

(*b*) Show shear strength of seam welds in units of 100 pounds per linear inch, thus:



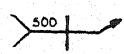
4. Butt Welds

(*a*) Show resistance butt welds without bead weld symbol signifying that weld is not made from any side, but all at once, thus (see II, 4*a*):



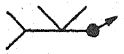
(*b*) Resistance butt welds assumed to be equal to strength of base metal in tension unless otherwise indicated.

(*c*) When a different strength is desired, show strength of butt welds in tension in units of 100 pounds per square inch, thus:



IV Supplementary Symbols

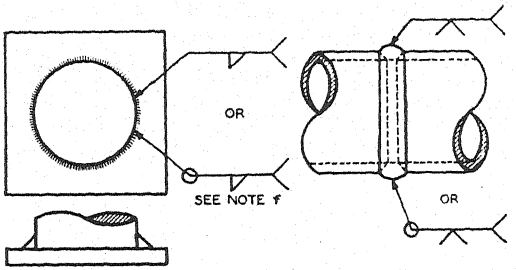
(*a*) Show "field" welds (any weld not made in shop) thus:



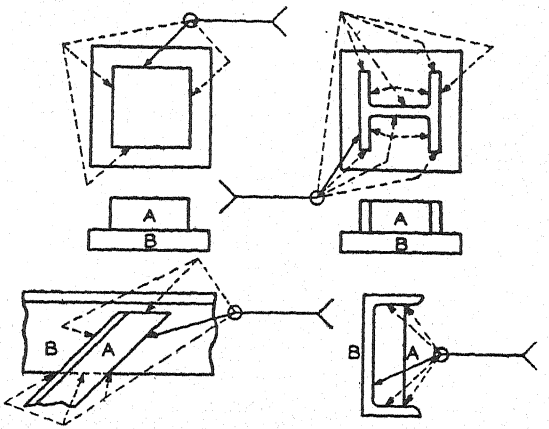
(*b*) Show "all around" welds, weld encircling joint (or joints) in so far as is possible, thus:



(*c*) When the weld encircles the joint but there is no abrupt change in the direction of the joint or parts of the joint (changes in the direction of rolled structural sections are considered abrupt even though there are fillets in the corners), the all-around symbol may or may not be used as desired, thus:

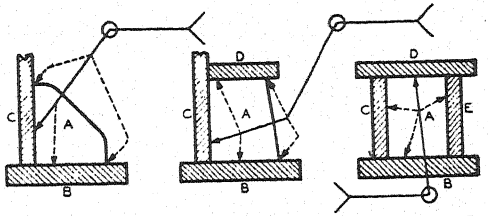


(*d*) The all-around symbol extends control of the welding symbol beyond abrupt changes in the direction of one joint, or parts of one joint, to encirclement of the complete joint in so far as is possible, thus:



ONE JOINT BETWEEN TWO MEMBERS "A" AND "B"

(*e*) The all-around symbol extends the control of the welding symbol not only beyond abrupt changes in the direction of one joint, but to two or more joints to the encirclement of the joints in so far as is possible, thus:

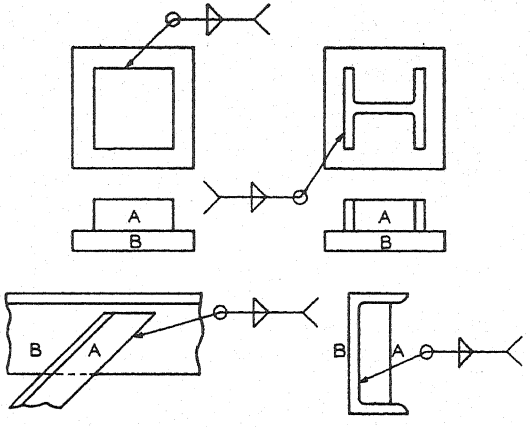


TWO JOINTS AB, AND AC BETWEEN 3 MEMBERS A, B AND C

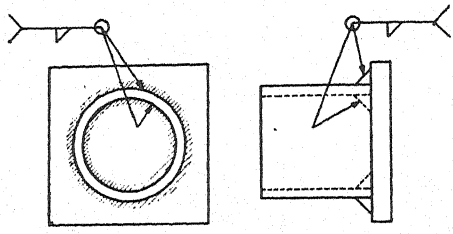
THREE JOINTS AB, AC, AND AD BETWEEN 4 MEMBERS A,B,C AND D.

FOUR JOINTS AB, AC, AD, AND AE BETWEEN 5 MEMBERS A,B,C,D AND E.

(*f*) When the use of an arrow-side or other-side symbol, together with an all-around symbol, results in a weld on both sides of the joint as a whole, it is advisable to use the both-sides symbol, thus, even though a one-side symbol may be strictly correct: See (*g*) below.



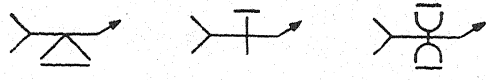
(*g*) When the member involved is hollow or annular and there is more than one encircling weld, and there is likelihood of confusion existing as to whether or not a both-sides symbol would refer to a part of the joint or to the joint as a whole, show each encircling weld with a separate arrow, thus:



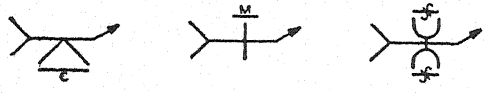
(*h*) The locations of the flush and finish symbols have the usual arrow and other (near and far) side significance and govern only the sides on which they are shown.

(*i*) Finish marks govern faces of welds only and not base metal either before or after welding.

(*j*) Show arc and gas welds made flush without recourse to any kind of finishing, thus:



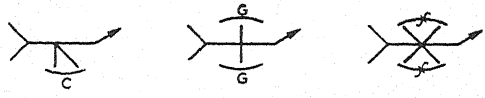
(*k*) Show arc and gas welds made flush by mechanical means with both flush and user's standard finish symbols, thus:



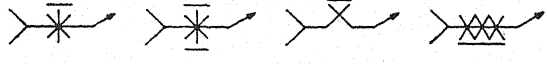
The following letters are suggested for indicating finishing processes:

C—Chip G—Grind M—Machine

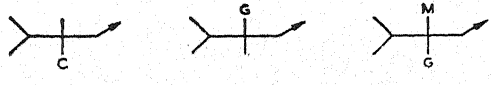
(*l*) Show finishing on face of arc and gas welds, which need not be flush, with user's standard finish symbols on bead symbol, thus:



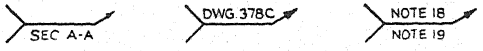
(*m*) Show spot, seam or projection welds made practically flush (with minimum indentation), thus:



(*n*) Show resistance butt welds, finished by mechanical means, without flush symbol, thus:



(*o*) Show special welds not covered by any of the above symbols by a detailed section or reference drawing, or give any supplementary information by means of a note and refer weld to section, drawing, or note by a reference symbol. Reference symbol has usual location significance, thus:



PERSONNEL OF COMMITTEE ON SYMBOLS

L. C. Bibber (*Chairman*)..... Carnegie-Illinois Steel Corp.
W. A. Bischoff..... Bell Telephone Laboratories
Bureau of Ships..... Navy Department
A. M. Candy..... Hollup Corporation
R. W. Clark..... General Electric Company
H. O. Hill..... Bethlehem Steel Company
C. H. Jennings..... Westinghouse Electric & Mfg. Co.
A. B. S. Kvaal (Alternate)..... Bell Telephone Laboratories
G. Mikhalapov..... The Taylor-Winfield Corp.
C. W. Obert..... The Linde Air Products Co.
H. M. Priest..... Railroad Research Bureau

CHAPTER 44

TESTING TERMS, PHYSICAL CONSTANTS AND CONVERSION TABLES*

Testing Terms

IN TENSILE and compressive tests the stresses are computed on the basis of the original cross-sectional area of the specimen; in transverse and torsional tests the stress in the extreme fiber is computed from the flexural and torsional formulas.

Definitions of mechanical properties of materials and methods of testing are in general conformity with the standard methods for testing of the American Society for Testing Materials.[1]

1. *Proportional Limit.*—Stress at which the deformation ceases to be proportional to the load as determined by strainometer (extensometer for tension, compressometer for compression and deflectometer for transverse tests, value being read from plotted results).

2. *Elastic Limit.*—In tensile and compressive tests: The stress at which the initial permanent elongation or shortening of the gage length occurs, as shown by an instrument of high precision (determined from set readings with extensometer or compressometer). In transverse tests: The extreme fiber stress at which the initial permanent deflection occurs as determined with a deflectometer.

Tests are rarely made to determine the elastic limit, since such tests involve repeated application and release of load and require considerable time. For practical purposes the elastic limit may be regarded as equal to the proportional limit.

NOTE: The proportional limit and elastic limit are indefinite and widely different values may be reported for the same material unless definite limits are prescribed for the minimum departure from a straight line or the minimum permanent set which shall be considered significant.

3. *Yield Point.*—Stress at which marked increase in deformation of specimen occurs without increase in load as determined usually by drop of beam or with dividers for tensile, compressive or transverse tests.

NOTE: Many ductile materials do not have a definite yield point. For these it is customary to define a yield strength:

* Conversion tables taken from Carnegie-Illinois Steel Corporation's *Pocket Companion.* Testing Terms taken from the Circular of the Bureau of Standards, No. 101, *Physical Properties of Materials,* with some revisions. Physical Constants taken from *Metals Handbook,* 1939.

[1] *A.S.T.M. Standards,* Part I, 776–780 (1939).

Yield strength—the stress at which a material exhibits a specified limiting permanent set. (See *A.S.T.M. Standards*, Part I, p. 778 (1939).)

4. Tensile Compressive or Shearing Strength.—Maximum stress developed in the material during test, load being referred to the original cross-section.

5. Modulus of Rupture.—Maximum stress in the extreme fiber of a beam tested to rupture as computed by the application of the flexural formula to stresses above the transverse proportional limit. For simple rectangular beam with concentrated center load it equals

$$S = \frac{1.5 \times \text{load} \times \text{span}}{\text{area} \times \text{depth}}$$

6. Torsional Strength (or Modulus of Rupture in Torsion).—Maximum stress in the extreme fiber of a specimen tested to rupture as computed by the application of the torsional formula to stresses above the torsional proportional limit. For a round specimen it equals

$$S = \frac{5.1 \times \text{twisting moment}}{\text{diameter}^3}$$

In ductile materials the stress at rupture may be considered uniformly distributed over the cross-sectional area and the above formula assumes the form

$$S = \frac{3.82 \times \text{twisting moment}}{\text{diameter}^3}$$

7. Elongation.—The percentage of elongation is found by dividing the increase of length after rupture by the original gage length. The percentage of elongation depends on the gage length. The elongation indicates the ductility of the material.

8. Reduction of Area.—The percentage of reduction of area is found as the ratio of the difference between the original and broken area of the cross-section to the original area. Reduction of area indicates generally the ductility of the material.[2]

9. Poisson's Ratio.—The ratio of lateral contraction per unit of diameter to longitudinal extension per unit of length of a bar under tension within the elastic limit of material.

10. Modulus of Elasticity in Tension or Compression.[3]—Ratio of stress within the proportional limit to the corresponding strain as determined with a precise extensometer. Accurate determinations of the modulus of elasticity are made with a gage length at least 8 in. (203.2 mm.) in length.

11. Modulus of Elasticity in Shear.[4]—Ratio of stress within the proportional limit to the corresponding angular strain (in radians). The following theoretical relation exists between the modulus of elasticity in shear and the modulus of elasticity

$$G = \frac{E}{2(1 + \lambda)}$$

where G is the modulus of elasticity in shear, E, modulus of elasticity and λ, Poisson's ratio.

[2] Some authors consider the reduction of area as a measure of toughness.
[3] Also known as Young's modulus (called in this chapter modulus of elasticity).
[4] Often called the modulus of rigidity.

It is difficult to make a direct experimental determination of G on account of the presence of other stresses. It is usually determined by the torsion of a round bar.

12. Brinell Number.—Ratio of load on a sphere used to indent the material to be tested to the area of the spherical indentation produced. The standard sphere used is a 10-mm. diam. hardened steel ball. The loads used are 3000 kg. (6615 lb.) for steel and 500 kg. (1102 lb.) for softer metals, and the time of application of load is 30 sec. Values shown in the tables are based on spherical areas computed in the main from measurements of the diameters of the spherical indentations, by the following formula:

$$Bn = \frac{P}{\pi t D} = \frac{P}{\frac{\pi D}{2}(D - \sqrt{D^2 - d^2})}$$

where P = load in kg.
t = depth of indentation.
D = diameter of ball.
d = diameter of indentation, all lengths being expressed in millimeters.

Brinell numbers have a certain relation to tensile strength, and these numbers may be used to determine tensile strengths approximately by employing the proper conversion factor for the material.

13. Erichsen Value.—Index of forming qualities of sheet metal. The test is conducted by supporting the sheet on a circular ring and deforming it at the center of the ring by a spherically pointed tool. The depth of impression (or cup), in millimeters, required to obtain fracture is the Erichsen value for the metal. Erichsen standard values for trade qualities of soft metal sheets, corresponding to various sheet thicknesses, are furnished by the manufacturer of the machine.[5]

14. Bend Test.—Angle through which the material can be bent without fracture or the number of bendings around a predetermined diameter is recorded. In some cases a minimum diameter around which the test piece can be bent through a certain angle is determined. Very valuable test indicating the ductility of malleable metals.

15. Impact Value.—Indicates the shock-resisting qualities of material. Is of particular value in ascertaining the influence of heat treatment. Impact value depends on the form of the specimen.[6]

16. Fatigue Resistance.—See Chapter 34C.

17. Resilience.—The potential energy of deformation of a body. The resilient materials are those which are capable of absorbing elastically a large amount of work done by the applied load. The resilience depends upon the elastic limit of material and upon its modulus of elasticity (in tension or in shear).

18. Ductile Materials.—Ductile materials are those which are capable of undergoing considerable permanent deformation while subjected to tensile stresses.

19. Plastic Materials.—Plastic materials are those which are capable of undergoing considerable permanent deformation under compressive stresses.

[5] *Proc. A.S.T.M.*, **17** (2), 200 (1917).
[6] For description of impact testing machines and specimens used by various investigators see Whittemore, H. L., "Bibliography on Impact Testing," *Proc. A.S.T.M.*, 1922.

20. Malleable Materials.—Malleable materials are those which can be hammered into thin sheets without rupture.

21. Brittle Materials.—Brittle materials are those which show little permanent deformation when stressed to rupture.

22. Stiff Materials.—Stiff materials are those which have a high modulus of elasticity. They deform little, if subjected to stresses not exceeding the elastic limit.

23. Flexible Materials.—Flexible materials are those which have a low modulus of elasticity. They can be deformed considerably by bending, twisting, etc., within the elastic limit of material.

24. Tough Materials.—Tough materials are those which will withstand heavy shocks or will absorb a large amount of energy.

25. Soft Materials.[7]—Soft materials are those which offer little resistance to indenting or scratching.

26. Hard Materials.[7]—Hard materials are those which offer great resistance to indenting or scratching.

Physical Constants of Important Elements

Elements	Symbol	Density Lb./In.³ at 68°F.	Melting Point, °F.	Elements	Symbol	Density Lb./In.³ at 68°F.	Melting Point, °F.
Aluminum	Al	0.0975	1214.6	Mercury	Hg	0.489	−38.0
Antimony	Sb	0.2391	1166.9	Molybdenum	Mo	0.368	4748
Argon	A	.....	−306.2	Neon	Ne	3.03×10^{-5}	−415.498
Arsenic	As	0.2070	1497	Nickel	Ni	0.322	2646
Barium	Ba	0.1265	1562	Nitrogen	N	4.209×10^{-5}	−345.87
Beryllium	Be	0.0658	2345	Oxygen	O	4.8122×10^{-5}	−361.12
Bismuth	Bi	0.3541	519.8	Phosphorus	P	0.0657	111.4
Boron	B	0.0831	4172	Platinum	Pt	0.774	3224
Cadmium	Cd	0.3125	609.6	Potassium	K	0.031	144.1
Calcium	Ca	0.0560	1564	Radium	Ra	0.1808	1760
Carbon	C	0.0802	....	Selenium	Se	0.174	428
Chromium	Cr	0.2579	2822	Silicon	Si	0.087	2600
Cobalt	Co	0.3216	2714	Silver	Ag	0.38	1761
Columbium	Cb	0.3096	3542	Sodium	Na	0.035	207.5
Copper	Cu	0.323	1981.4	Sulphur	S	0.075	235.4
Hydrogen	H	0.3026×10^{-5}	−434.4	Tantalum	Ta	0.60	5162
Iridium	Ir	0.809	4368	Tellurium	Te	0.224	846
Iron	Fe	0.284	2795	Tin	Sn	0.264	449.6
Krypton	Kr	3.502×10^{-3}	−275.22	Titanium	Ti	0.163	3272
Lead	Pb	0.409	621.2	Tungsten	W	0.698	6098
Magnesium	Mg	0.0628	1204	Vanadium	V	0.205	3110
Manganese	Mn	0.268	2268	Zinc	Zn	0.258	787.0

METRIC CONVERSION FACTORS

Inches to Centimeters—1 in. = 2.540005 cm.
Inches² to Centimeters²—1 in.² = 6.451625 cm.²
Inches³ to Centimeters³—1 in.³ = 16.38716 cm.³
Inches⁴ to Centimeters⁴—1 in.⁴ = 41.62347 cm.⁴
Centimeters to Inches—1 cm. = 0.3937 in.
Centimeters² to Inches²—1 cm.² = 0.15499969 in.²
Centimeters³ to Inches³—1 cm.³ = 0.0610234 in.³
Centimeters⁴ to Inches⁴—1 cm.⁴ = 0.0240249 in.⁴
Feet to Meters—1 ft. = 0.3048006 m.
Pounds per Foot to Kilograms per Meter—1 lb. per ft. = 1.488161 kg. per m.
Pounds per Sq. Inch to Kg. per Sq. Cm.—1 lb. per in.² = 0.0703067 kg. per cm.²
Inch-Pounds to Kilogram-Centimeters—1 in.-lb. = 1.152127 kg.-cm.
Meters to Feet—1 m. = 3.2808333 ft.

[7] "Soft" and "hard" are indefinite terms which acquire a definite relative meaning when a definite hardness test is specified.

Kilograms per Meter to Pounds per Foot—1 kg. per m. = 0.67197 lb. per ft.
Kg. per Sq. Cm. to Pounds per Sq. Inch—1 kg. per cm.^{2} = 14.2234 lb. per in.^{2}
Kilogram-Centimeters to Inch-Pounds—1 kg. cm. = 0.86796 in.-lb.

CONVERSION TABLES

LENGTHS

1 meter (m) = 10 decimeters (dm) = 100 centimeters (cm) = 1000 millimeters (mm).
1 meter (m) = 0.1 decameter (dkm) = 0.01 hectometer (hm) = 0.001 kilometer (km).
1 meter (m) = 39.37 inches, U. S. Standard = 39.370113 inches, British Standard.
1 millimeter (mm) = 1000 microns (μ) = 0.03937 inch = 39.37 mils.

Meters, m	Inches, in.	Feet, ft.	Yard, yd.	Rods, r.	Chains, ch.	Miles, U. S.		Kilometers, km
						Statute	Nautical	
1	39.37	3.28083	1.09361	0.19884	0.04971	$0.^{3}6214$	$0.^{3}5396$	0.001
0.02540	1	0.08333	0.02778	$0.^{2}5051$	$0.^{2}1263$	$0.^{4}1578$	$0.^{4}1371$	$0.^{4}2540$
0.30480	12	1	0.33333	0.06061	0.01515	$0.^{3}1894$	$0.^{3}1645$	$0.^{3}3048$

Notations $^{2}0$, $^{3}0$, $^{4}0$, etc., indicate that the $^{2}0$, $^{3}0$, $^{4}0$, etc., are to be replaced by 2, 3, 4, etc., ciphers.

SURFACES AND AREAS

1 sq. meter (m^2) = 100 sq. decimeters (dm^2) = 10000 sq. centimeters (cm^2).
1 sq. meter (m^2) = 0.01 are (a) = 0.0001 hectare (ha)
1 sq. millimeter (mm^2) = 0.01 cm^2 = 0.00155 sq. inch = 1973.5 circular mils.
1 are (a) = 1 sq. decameter (dkm) = 0.0247104 acre.

Sq. Meters, m^2	Sq. Inches, sq. in.	Sq. Feet, sq. ft.	Sq. Yards, sq. yd.	Sq. Rods, sq. r.	Acres, A	Hectares, ha.	Sq. Miles, Statute	Sq. Kilometers, km^2
1	1550.00	10.7639	1.19599	0.03954	$0.^{3}2471$	0.0001	$0.^{6}3861$	$0.^{5}1$
$0.^{3}6452$	1	$0.^{2}6944$	$0.^{3}7716$	$0.^{4}2551$	$0.^{6}1594$	$0.^{7}6452$	$0.^{9}2491$	$0.^{9}6452$
0.09290	144	1	0.11111	$0.^{2}3673$	$0.^{4}2296$	$0.^{5}9290$	$0.^{7}3587$	$0.^{7}9290$

Notations $^{2}0$, $^{3}0$, $^{4}0$, etc., indicate that the $^{2}0$, $^{3}0$, $^{4}0$, etc., are to be replaced by 2, 3, 4, etc., ciphers.

VOLUME AND CAPACITY

1 cu. meter (m^3) = 1000 cu. decimeter (dm^3) = 1000000 cu. centimeters (cm^3).
1 liter (l) = 10 deciliters (dl) = 100 centiliters (cl) = 1000 milliliters (ml) = 1000 cu. centimeters (cm^3 or c.c.)
1 liter (l) = 0.1 decaliter (dkl) = 0.01 hectoliter (hl) = 1 cu. decimeter (dm^3).

Cubic Decimeters, dm^3 or Liters, l	Cubic Inches, cu. in.	Cubic Feet, cu. ft.	Cubic Yards, cu. yd.	U. S. Quarts		U. S. Gallons		U. S. Bushels, bu.
				Liquid, l. qt.	Dry, d. qt.	Liquid, l. gal.	Dry, d. gal.	
1	61.0234	0.03531	$0.^{2}1308$	1.05668	0.90808	0.26417	0.22702	0.02838
0.01639	1	$0.^{3}5787$	$0.^{4}2143$	0.01732	0.01488	$0.^{2}4329$	$0.^{2}3720$	$0.^{3}4650$
28.3170	1728	1	0.03704	29.9221	25.7140	7.48055	6.42851	0.80356

Notations $^{2}0$, $^{3}0$, $^{4}0$, etc., indicate that the $^{2}0$, $^{3}0$, $^{4}0$, etc., are to be replaced by 2, 3, 4, etc., ciphers.

CONVERSION TABLES

MASSES AND WEIGHTS

1 gram (g) = 10 decigrams (dg) = 100 centigrams (cg) = 1000 milligrams (mg.)
1 gram (g) = 0.1 decagram (dkg) = 0.001 hectogram (hg) = 0.001 kilogram (kg)
1 kilogram (kg) = 1 cu. decimeter of water or liter (4°C., 45° Lat. and sea level) = 15432.35639 grains, U. S. and British Standard.

Kilograms, kg	Grains, gr.	Ounces		Pounds		Tons		
		Troy, oz. t.	Avoir., oz. av.	Troy, lb. t.	Avoir., lb. av.	Net, (Short), 2000 lbs.	Gross, (Long), 2240 lbs.	Metric, 1000 kg
1	15432.4	32.1507	35.2740	2.67923	2.20462	$0.^{2}1102$	$0.^{3}9842$	0.001
$0.^{4}6480$	1	$0.^{2}2083$	$0.^{2}2286$	$0.^{3}1736$	$0.^{3}1429$	$0.^{7}7143$	$0.^{7}6378$	$0.^{7}6480$
0.03110	480	1	1.09714	0.08333	0.06857	$0.^{4}3429$	$0.^{4}3061$	$0.^{4}3110$
0.02835	437.5	0.91146	1	0.07595	0.06250	$0.^{4}3125$	$0.^{4}2790$	$0.^{4}2835$
0.37324	5760	12	13.1657	1	0.82286	$0.^{3}4114$	$0.^{3}3674$	$0.^{3}3732$
0.45359	7000	14.5833	16	1.21528	1	0.00050	$0.^{3}4464$	$0.^{3}4536$
907.185	14000000	29166.7	32000	2430.56	2000	1	0.89286	0.90719
1016.05	15680000	32666.7	35840	2722.22	2240	1.12	1	1.01605
1000	15432356	32150.7	35274.0	2679.23	2204.62	1.10231	0.98421	1

Notations $^{2}0$, $^{3}0$, $^{4}0$, etc., indicate that the $^{2}0$, $^{3}0$, $^{4}0$, etc., are to be replaced by 2, 3, 4, etc., ciphers.
EXAMPLE. 1 grain = $0.^{2}2083$ = 0.002083 oz. t. 1 grain = $0.^{4}6480$ = 0.00006480 kg.

FORCES OR WEIGHTS PER UNITS OF LENGTH (LINEAR WEIGHTS)

1 dyne per centimeter = 0.00101979 g/cm = 0.000183719 poundal/in.
1 gram per centimeter = 980.5966 dynes/cm = 0.180154 poundal/in.
1 poundal per inch = 5443.11 dynes/cm = 5.55081 g/cm = 0.0310832 pound/in.

Grams per Centimeter, g/cm	Grains per Inch, gr./in.	Pounds per Inch, lb./in.	Pounds per Foot, lb./ft.	Pounds per Yard, lb./yd.	Kilograms per Meter, kg/m	Net Tons, (2000 lbs.), per Mile	Gross Tons, (2240 lbs.), per Mile	Metric Tons, (1000 kg), per Kilometer
1	39.1983	$0.^{2}5600$	0.06720	0.20159	0.10	0.17740	0.15839	0.10
0.02551	1	$0.^{3}1429$	$0.^{2}1714$	$0.^{2}5143$	$0.^{2}2551$	$0.^{2}4526$	$0.^{2}4041$	$0.^{2}2551$
178.579	7000	1	12	36	17.8579	31.6800	28.2857	17.8579
14.8816	583.333	0.08333	1	3	1.48816	2.64000	2.35714	1.48816

Notations $^{2}0$, $^{3}0$, $^{4}0$, etc., indicate that the $^{2}0$, $^{3}0$, $^{4}0$, etc., are to be replaced by 2, 3, 4, etc., ciphers.

FORCES OR WEIGHTS PER UNITS OF AREA (PRESSURE)

1 dyne per sq. centimeter = 0.00101979 g/cm² = 0.000466646 poundals/in².
1 gram per sq. centimeter = 980.5966 dynes/cm² = 0.457592 poundals/in².
1 poundal per sq. inch = 2142.95 dynes/cm² = 2.18536 g/cm² = 0.0310832 pound/in².

Kilograms per Sq. Centimeter, kg/cm²	Pounds per Sq. Inch, lb./in.²	Pounds per Sq. Foot, lb./ft.²	Net Tons, (2000 lbs.), per Sq. Foot	Atmospheres, Standard, 760 mm	Columns of Mercury, (Hg) 13.59593 Sp. G.		Columns of Water, Max. Density 4° C	
					Millimeters	Inches	Meters	Feet
1	14.2234	2048.17	1.02408	0.96778	735.514	28.9572	10	32.8083
0.07031	1	144	0.07200	0.06804	51.7116	2.03588	0.70307	2.30665
$0.^{3}4882$	$0.^{2}6944$	1	0.00050	$0.^{3}4725$	0.35911	0.01414	$0.^{2}4882$	0.01602

Notations $^{2}0$, $^{3}0$, $^{4}0$, etc., indicate that the $^{2}0$, $^{3}0$, $^{4}0$, etc., are to be replaced by 2, 3, 4, etc., ciphers.

FORCES OR WEIGHTS PER UNITS OF VOLUME (DENSITY)

1 dyne per cu. centimeter = 0.00101979 gram/cm³ = 0.00118528 poundals/in³.
1 gram per cu. centimeter = 980.5966 dynes/cm³ = 1.162283 poundals/in³.
1 poundal per cu. inch = 843.683 dynes/cm³ = 0.860378 g/cm³ = 0.0310832 pound/in³.

Grams per Cu. Centimeter, g/cm³	Pounds per Cu. Inch, lb./in.³	Pounds per Cu. Foot, lb./ft.³	Pounds per Cu. Yard, lb./yd.³	Kilograms per Cu. Meter, kg/m³	Pounds per Bushel, U. S.	Pounds per Gallon, Dry, U. S.	Pounds per Gallon, Liquid, U. S.	Kilograms per Hectoliter kg/hl
1	0.03613	62.4283	1685.56	1000	77.6893	9.71116	8.34545	100
27.6797	1	1728	46656	27679.7	2150.42	268.803	231	2767.97
0.01602	$0.^{3}_{0}5787$	1	27	16.0184	1.24446	0.15556	0.13368	1.60184

Notations $^{2}_{0}$, $^{3}_{0}$, $^{4}_{0}$, etc., indicate that the $^{2}_{0}$, $^{3}_{0}$, $^{4}_{0}$, etc., are to be replaced by 2, 3, 4, etc., ciphers.
EXAMPLE. 1 kg/m³ = $0.^{4}_{0}3613$ = 0.00003613 lb./in³.

ENERGY, WORK, HEAT

1 dyne-centimeter = 1 erg = 0.00101979 gram-centimeter = $0.^{7}_{0}737612$ foot-pound.
1 gram-centimeter = 980.5966 ergs = $0.^{4}_{0}7233$ foot-pound.
1 foot-pound = 13557300 ergs = 13825.5 gram-centimeters.

Kilogram-meters, kg-m	Foot-Pounds, ft.-lbs.	Horsepower-hour		Poncelet-hours, 100 kg-m-h	Kilowatt-hours, kw-h	Joules, 10^{7} ergs, J=S	Thermal Units	
		U. S., H. P.-h	Metric, 75 kg-m-h				B. T. U.	Calories, kg-cal
1	7.23300	$0.^{5}_{0}3653$	$0.^{5}_{0}3704$	$0.^{5}_{0}2778$	$0.^{5}_{0}2724$	9.80597	$0.^{2}_{0}9296$	$0.^{2}_{0}2342$
0.13826	1	$0.^{6}_{0}5051$	$0.^{6}_{0}5121$	$0.^{6}_{0}3840$	$0.^{6}_{0}3766$	1.35573	$0.^{2}_{0}1285$	$0.^{3}_{0}3239$

Notations $^{2}_{0}$, $^{3}_{0}$, $^{4}_{0}$, etc., indicate that the $^{2}_{0}$, $^{3}_{0}$, $^{4}_{0}$, etc., are to be replaced by 2, 3, 4, etc., ciphers.

POWER, RATE OF ENERGY AND HEAT

1 erg per sec. = 1 dyne-cm/sec. = 0.00101979 gram-cm/sec. = $0.^{7}_{0}737612$ foot-pound/sec.
1 gram-centimeter per second = 980.5966 ergs/sec. = $0.^{4}_{0}7238$ foot-pound/sec.
1 foot-pound per second = 13557300 ergs/sec = 13825.5 gram-cm/sec.

Kilogram-meters per Second, kg-m/sec.	Foot-pounds per Second, ft.-lbs./sec.	Horsepower		Poncelet, 100 kg-m/sec.	Kilowatt, kw.	Watts, 10^{7} ergs/sec.	Thermal Units per Sec.	
		U. S., 550 ft.-lbs./sec.	Metric, 75 kg-m/sec.				B.T.U./sec.	kg-cal/sec.
1	7.23300	0.01315	0.01333	0.01	$0.^{2}_{0}9806$	9.80597	$0.^{2}_{0}9296$	$0.^{2}_{0}2342$
0.13826	1	$0.^{2}_{0}1818$	$0.^{2}_{0}1843$	$0.^{2}_{0}1383$	$0.^{2}_{0}1356$	1.35573	$0.^{2}_{0}1285$	$0.^{3}_{0}3237$

Notations $^{2}_{0}$, $^{3}_{0}$, $^{4}_{0}$, etc., indicate that the $^{2}_{0}$, $^{3}_{0}$, $^{4}_{0}$, etc., are to be replaced by 2, 3, 4, etc., ciphers.

VELOCITIES AND ACCELERATIONS

1 kine = 1 centimeter per second = 0.0328083 foot per second.
1 radian per second = 57.2958 degrees per sec. = 0.159155 revolutions per sec.
1 gravity = 980.5966 centimeters per sec. per sec. = 32.1717 feet per sec. per sec.

Meters per Second, m/sec.	Feet per Second, ft./sec.	Miles per Hour, M/h	Knots per Hour, U. S.	Kilometers per Hour, km/h	Meter per Sec. per Sec. m/sec./sec.	Feet per Sec. per Sec. ft./sec./sec.	Miles per Hour per Sec. M/h/sec.	Kilometers per Hour per Sec. km/h/sec.
1	3.28083	2.23693	1.94254	3.6	.....	.....	.....	.....
0.30480	1	0.68182	0.59209	1.09728	.....	.....	.....	.....
0.44704	1.46667	1	0.86839	1.60935	.....	.....	.....	.....
0.51479	1.68894	1.15155	1	1.85325	.....	.....	.....	.....
0.27778	0.91134	0.62137	0.53959	1	.....	.....	.....	.....
.....	.....	.....	.....	.....	1	3.28083	2.23693	3.6
.....	.....	.....	.....	.....	0.30480	1	0.68182	1.09728
.....	.....	.....	.....	.....	0.44704	1.46667	1	1.60935
.....	.....	.....	.....	.....	0.27778	0.91134	0.62137	1

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